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Jan Akmal

Investigation of Optical Distance Sensors for Applications in Tool Industry

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Abstract

Author: Jan Sher Akmal

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Instructors: Prof. Dr. Udo Behn, University of Applied Sciences Schmalkalden

Deg. Programme Manager Jukka Nisonen, Saimaa University of Applied Sciences

Dipl.-Phys. Mr. Heinz-Wolfgang Lahmann,
Dipl.-Ing. Mr. René Linde ,The Society of Production Engineering and Development (GFE)

Keywords: Mechanical Inspection probe, confocal chromatic sensor, laser triangulation sensor.

The objective of the study was to increase the productivity of a Computer Numerical Controlled Machine used for measurement process followed by machining process. The machining process of the CNC machine was inevitably fixed due to machining parameters. However, it was possible to decrease the time of measuring process by replacing its mechanically operated, contact probe, displacement measurement system with an optically operated non-contact laser triangulation or confocal chromatic displacement measurement system.

The work was commissioned by the GFE and both measurement systems were bought. The additional required parts were made in the workshop. Several experiments were conducted in order to define the most suitable and compatible measurement system with the most efficient timing for the required CNC Machine. The selected measurement system was further tested and upgraded to achieve paramount results.

As a result of this thesis, an optically operated, non-contact laser triangulation, displacement measurement system proved to be the most suitable, affordable, and compatible to decrease in process measurement time in order to increase productivity.

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Terminology and Constants

MR	Measuring Range
SMR	Start of Measuring Range
MMR	Middle of Measuring Range
EMR	End of Measuring Range
CNC	Computerized Numerical Control
CCD	Charge Coupled Device
DSP	Digital Signal Processor
FPGA	Field Programmable Gate Array
FSO	Full Scale Output
mm	Millimeters
µm	Micrometers
um	Micrometers

1. Introduction

As technology develops, so does the demand for the quality of products. In order to fulfill such a requirement, measurements are made with tools of increasing accuracies and precisions to micron resolution of hard to reach surfaces even when these surfaces cannot be touched or seen with a naked eye. The measure of the production efficiency the productivity, is also taken into consideration as it determines the available technology for converting resources into outputs in a certain time demanded in an economy. Consequently, the development of new technologies pushes existing technologies to adapt to such required demands to keep up with the growing competition. The main purpose of this thesis is to investigate the use of optical distance sensors for applications in the tool industry to meet such demands.

1.1. Motivation

The objective of this thesis is to investigate optical distance sensors to decrease machine down time of CNC machines in order to increase their productivity. As the machining process of most machines is inevitably fixed due to machining parameters, it is possible to decrease the process measurement time in order to decrease machine down time thus increase productivity.

Four optical distance sensors, one confocal chromatic sensor and three laser triangulation sensors are thoroughly investigated to replace a mechanical inspection probe system to reduce its lengthy process measurement time. These optical sensors are integrated with two CNC machines to investigate their affordability, reliability, accuracy and precision. Unified Python programs for optimizing the configuration and settings are written for each optical sensor with the selected CNC machine and the results are taken accordingly to distinguish the most reliable optical measurement system. A usage diagram, an activity diagram and state diagrams were also made for the most efficient optical distance measurement system for better understanding of the Python programming scripts and for recommendations of the measurement cycle. The most suitable and efficient optical measurement sensor is further investigated and tested with a better CNC machine for paramount results for measuring displacement of different work pieces and for detecting rising and falling edges.

2. Physical Background

The three measurement principles described in this thesis are the mechanical probe measurement system, the optical confocal chromatic measurement system and the optical laser triangulation measurement system. A CNC machine with a specific resolution was used to investigate the optical measurement principles. Another CNC machine with a higher resolution was used for further investigation of the selected optical measurement system.

2.1. Mechanical Inspection Probe

A mechanical inspection probe shown in Figure 1 is attached to the spindle or tool of the CNC machine used in order to determine the location and orientation of products during the setting and to inspect the size and position of critical features for verification and process control. It achieves such objectives by physically sensing a series of discrete points on the surface of the component.

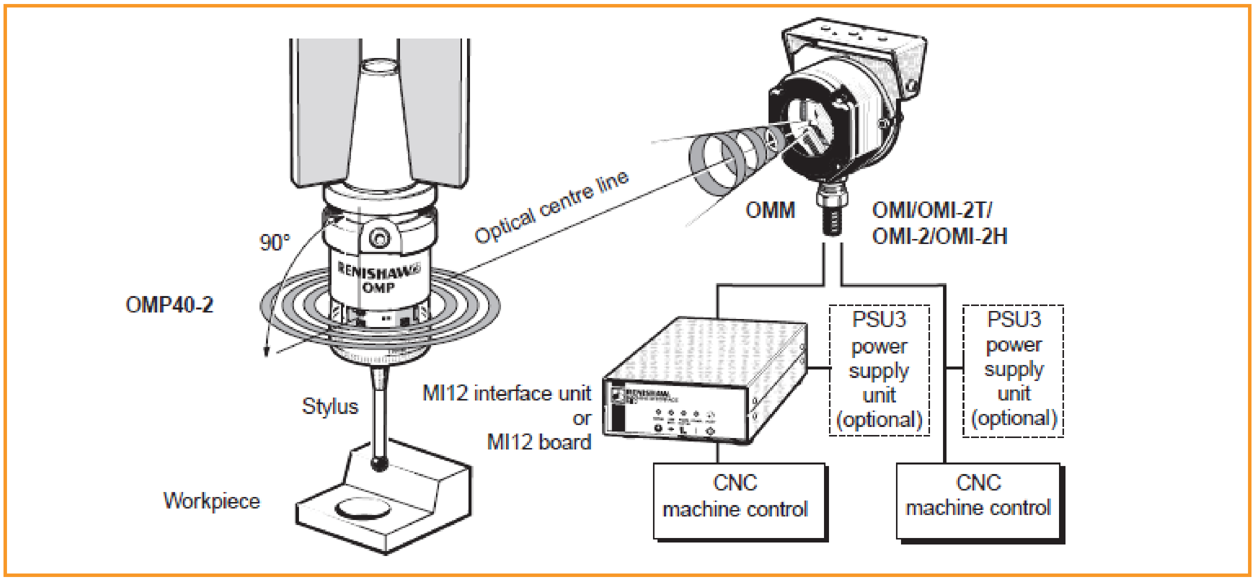


Figure 1 *OMP40-2 inspection probe system with optical transmission (13)*

2.1.1. Contact Probe Principle

A trigger signal is activated when the probe's stylus meets the surface of the part. The trigger signal is transferred to the CNC machine for further processing via a fast remote transmission system depending on the model. The transmission system defines the compatibility and reliability for sending the trigger signal to the CNC machine in order to avoid damage to the probe due to contact since it is mounted to the machine's spindle or tool. There are three main transmission types which include inductive transmission, optical (Infra-red) transmission and radio transmission. In each case the transmitter attached to the probe passes signals for the status of the probe whether it is in contact or not to a receiver which is hardwired to the machine's control cabinet. Inductive transmission is useful in cases where interconnecting wires are inconvenient, hazardous, or impossible due to rotational movements of the spindle or tool of the CNC machine. However, it has a very short range in contrast to optical and low power radio transmission which can transmit signals over a longer range of up to several meters. A line of sight is required by optical transmission from the transmitter to the receiver whereas it is not necessary for the radio transmission. In fact, the radio transmission takes advantage of the reflections and significant diffractions around the objects of the machine which makes it the most suitable transmission type for large multiple axis machines where line of sight is not always guaranteed. The line of sight for the optical transmission can be improved by introducing mirrors where line of sight is limited. (2, 12, 13)

2.1.2. OMP40-2 Inspection Probe

The inspection probe that needs to be replaced to decrease the process measurement time, 'OMP40-2' made by Renishaw, as seen in Figure 1, consists of a compact 3 dimensional touch trigger probe with 5 sensing directions which include ±X, ±Y and +Z. It has a ball diameter of 3 mm. It transmits data through optical transmission with a range of up to 5 meters. It has a theoretical repeatability of 1.0 µm at 480 mm/min with 50 mm stylus. It consists of a standard battery life of 140 hours of continuous use. (12, 13)

2.2. Optical Confocal Chromatic Measurement System

The optical confocal chromatic measurement system contains a confocal sensor and a controller which are connected with a fibre optic sensor cable as shown in Figure 2. The controller acts as a signal conditioning electronic by processing input signals from the sensor and can transmit output signals via RS232 digital interface, RS422 digital interface, universal serial bus or analog output for analysis depending on the model. It can be used for measuring displacement, distance, and even thickness along with in process quality control and dimensional testing in a wide range of industrial processes.

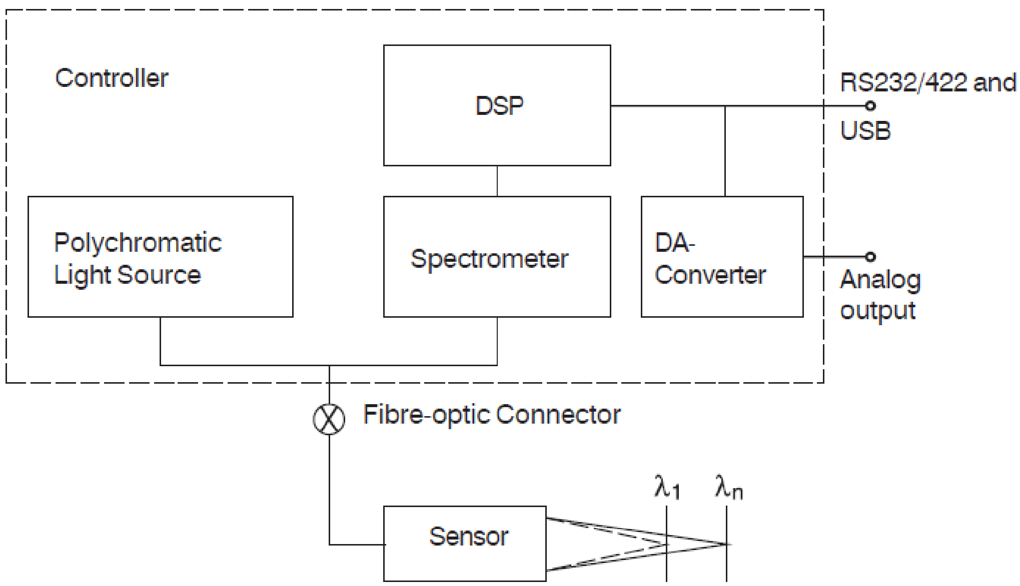


Figure 2 *Block diagram of a confocal chromatic measurement system (10)*

2.2.1. Confocal Chromatic Principle

In optics, confocal arrangement refers to the arrangement of two or more lenses when their focuses match. With the confocal chromatic measuring principle white light is focused onto an object through a multi-lens optical system as shown in Figure 3. The lenses are organized in such a way that the white light is dispersed into a monochromatic light by controlled chromatic aberration. Chromatic aberration or chromatic deviation, as shown in Figure 4a is a type of distortion in optical imaging in which there is a failure of a lens to focus all colors to the same convergence point. It occurs because lenses have different refractive indices for different wavelengths of the light due to the dispersion of the lens. The refractive index decreases with increasing wavelength. Since the focal length of a lens depends on the refractive index (see fig. 4b) different wavelengths of light will be focused onto different positions. Only the wavelength which is exactly focused onto the target surface is used for the measurement as a certain distance is assigned to each wavelength. The reflected light from the target surface is passed via a confocal aperture to the receiver which detects and processes the spectral changes and converts the light signals received from sensor to calculate displacements through its DSP. (7, 10, 15)

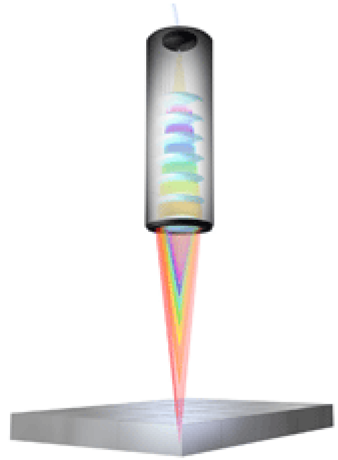


Figure 3 *Confocal chromatic principle (7)*

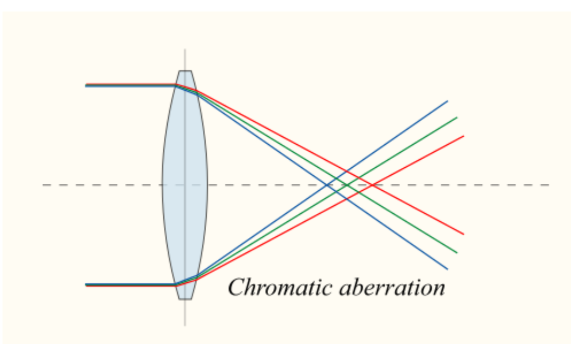


Figure 4a *Chromatic aberration (19)*

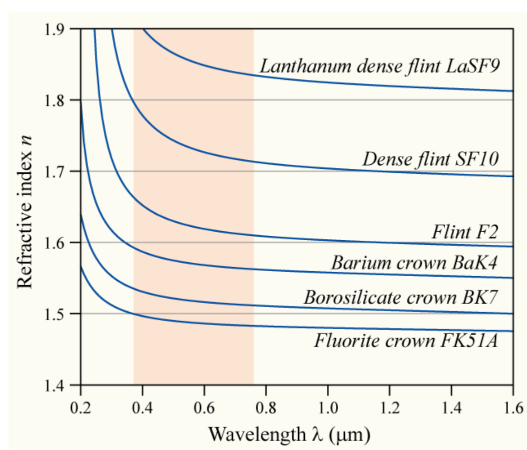


Figure 4b *Dispertion curve (18)*

2.2.2. The OptoNCDT2401 Confocal Sensor

The optical confocal measurement system, ‘’OptoNCDT2401’’, shown in Figure 5, was bought from Micro Epsilon and it was thoroughly investigated to measure the displacement over the surface of a specific part by integrating it with a CNC machine physically and digitally in order to test its reliability, accuracy and precision.

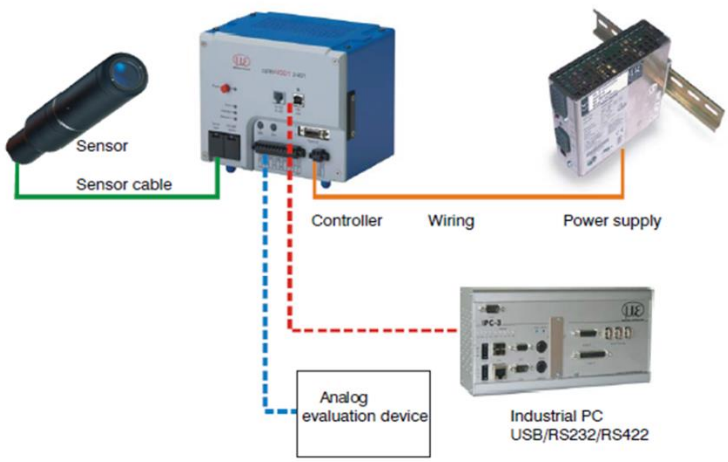


Figure 5 *The OptoNCDT2401 confocal chromatic sensor components (10)*

This sensor has a resolution of 0.9 micrometer which is incredibly precise. However, it has a start of measuring range (SMR) of 20.2 mm where no measurements can be taken, as shown in Figure 6. Furthermore, it has actual measuring range (MR) of 22 mm where measurements are processed. Therefore, it has an end of the measuring range (EMR) of 42.2 mm. Last but not least, the confocal chromatic sensor emits a spot diameter of 100 µm and it is capable of measuring the thickness of transparent materials if required. (4, 7)

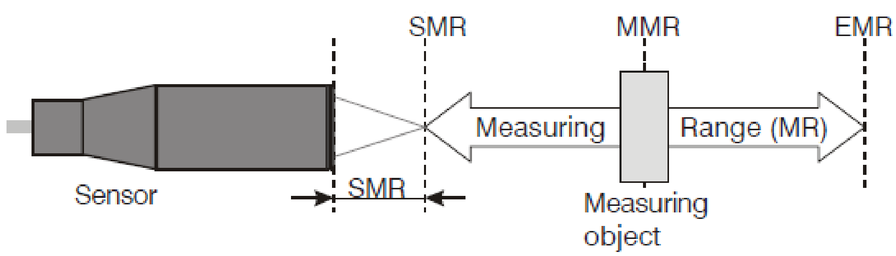


Figure 6 *Measuring range of the OptoNCDT2401 confocal chromatic sensor (10)*

2.3. Optical Laser Triangulation Measurement System

The optical laser triangulation measurement system consists of an optical laser sensor and signal conditioning electronics. It can be used for measuring displacement, distance, position and elongation in process quality control and dimensional testing in a variety of industrial processes.

2.3.1. Laser Triangulation Principle

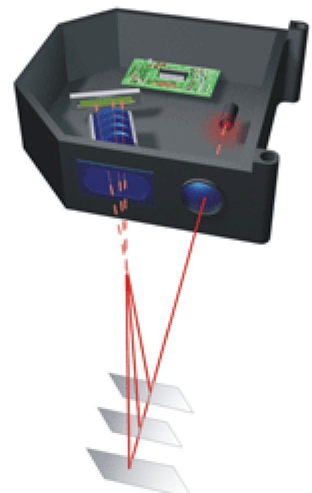


Figure 7 *Laser Triangulation Principle (8)*

The laser sensor uses the principle of optical triangulation which simply means measuring the distance by calculating the angle. A parallel beam of a diode laser is projected onto the target surface and the diffuse reflection of the light is detected by an optical receiver positioned at a certain angle to the optical axis of the laser beam onto a high sensitivity resolution element (CCD array) depending on the distance as shown in Figure 7. The distance to the target is calculated by a digital signal processor from the position of the light spot on the receiver element (CCD array) and from the distance of the transmitter to the receiving element. As the height increases the angle decreases and vice versa. Afterwards, the DSP signal is linearized and transmitted via analogue or digital interface depending on the requirements. The intensity of the diffuse reflection determines the signal from the high sensitivity resolution element (CCD array) which enables the sensor to compensate for changes in brightness on the object being measured. (1, 5, 8, 9)

2.3.2. The OptoNCDT1700-200 Laser Sensor

The optical laser triangulation measurement system, 'OptoNCDT1700-200' shown in Figure 8 is bought from Micro Epsilon. It was thoroughly investigated by integrating it with a CNC machine physically as well as digitally to test its reliability, accuracy and precision by measuring the displacement over specific parts. It uses the principle of optical triangulation and operates with a semiconductor laser with a wavelength of 670 nm which is visibly red. The laser is operated in a pulsed mode, where the pulse frequency corresponds to the measuring frequency. The pulse frequency can be adapted to the surface properties and it can form an almost stable beam which can be clearly seen with human eyes. The maximum optical power of the laser is ≤ 1 milliwatt. The sensor has a resolution of 12 µm. The start of measuring range (SMR) is 70 mm, the actual measuring range (MR) is 200 mm and hence the end of measuring range (EMR) is 270 mm with a 1.3 mm laser spot diameter. It also provides display and data transmission functions via the digital interface RS422 output, current output or analog output. (9)

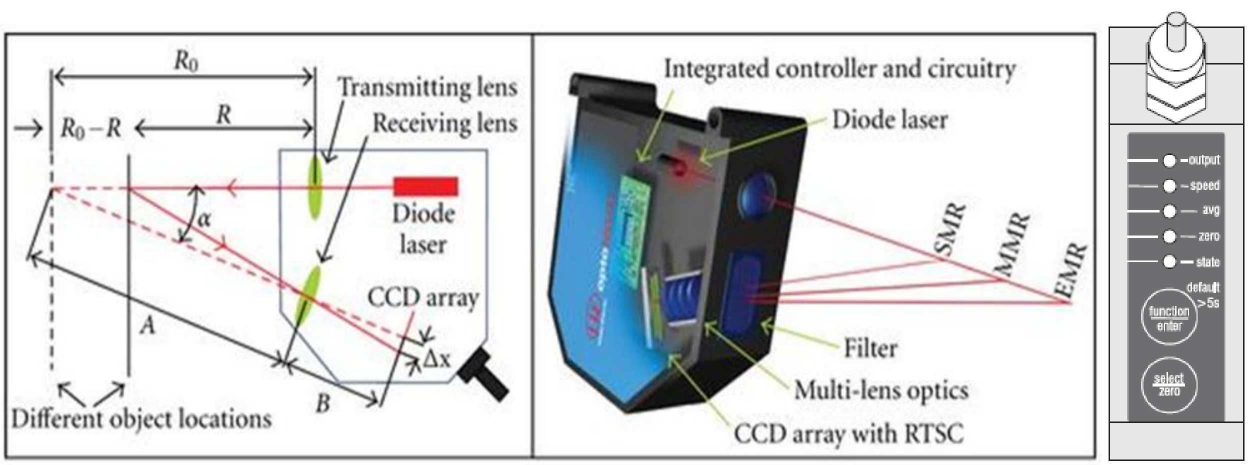


Figure 8 *The OptoNCDT1700 laser triangulation sensor components, measuring range (left) (3) and membrane keys (right) (9)*

2.4. CNC Machines

There are two CNC machines used to investigate optical distance sensors in this work as shown in Figure 9. They are micro-processor based micro-step control systems designed to control up to 3 to 5 axes depending on the machine and they are used for various industrial automation tasks including drilling, milling and handling objects. The first machine was used to investigate both sensors including the confocal chromatic sensor and the laser triangulation sensor. The second machine was used for further investigation of the selected most reliable, affordable, accurate and precise distance sensor. The first CNC machine system consists of 3 axis including X, Y and Z axis with a resolution of 25 micrometers. The definition of reference points and coordinate points is an essential requirement for programming the machine movements within the working areas of the machine tools. Therefore, the source code of CNC machine is written with a programmable language called Python on an operational Central Processing Unit with the required syntax and parameters. Furthermore, a serial interface to RS232 is used for data transfer between this CNC machine system and the controlled computer. The second CNC machine used for further investigation of the selected optical measurement system consisted of a tool which could move up to 5 axes including X, Y, Z axis and rotational movements. This CNC machine had a theoretical resolution of 1 µm which is 25 times more accurate than the first CNC machine used. It is used for edge detection analysis of the selected optical measurement system.

Figure 9 *CNC Machine 1 (Left) and CNC machine 2 (right)*

3. Advantages and Disadvantages of Measurement Systems

Before practical investigation and analysis of the measurement systems including the mechanical inspection probe, the confocal chromatic sensor and the laser triangulation sensor discussed in this work, the advantages and disadvantages of each measurement systems were taken into consideration in the following chapter.

3.1. Advantages and Disadvantages of Mechanical Inspection Probe

The inspection probe, OMP40-2 can be easily mounted to the tool of the CNC machine. It has a benefit of measuring omni directionally (±x, ±y, +z) in relatively dusty and wet working environment during machining in contrast to optical distance sensors. They require a thoroughly cleaned and dry working environment during measuring process. The stylus of the inspection probe is changeable in terms of size depending on the details of the measurements taken. It can also be replaced if it is damaged. In theory, its ability to transmit data up to 5 meters with a precision of 1 micrometer at 480 mm/min with 50 mm stylus can also be considered as its advantage.

The main setback of mechanical inspection probes is that they have a very slow feed rate or measurement frequency in comparison to optical distance sensors. Therefore, they take a very long time to measure the dimensions of a selected work piece. In addition as they are contact probes, they have a larger tendency to break and are more vulnerable to damage due to interference or delay in transmission in comparison to optical distance sensors. As their feed rate is quite slow, they increase machining downtime and therefore decrease productivity.

3.2. Advantages and Disadvantages of the Confocal Chromatic Sensor

This sensor has an exceptional resolution of 0.9 micrometer with a fast feed rate and measurement frequency of up to 2.0 kHz. It has the ability to measure the distance, displacement and even thickness of the material along with in process quality control and dimensional testing. Its small spot size can also be considered as an advantage. Furthermore it can transmit output signals via RS232 digital interface, RS422 digital interface, universal serial bus or analog output for analysis. The sensor is totally passive since it includes no heat sources or moving parts. Therefore, it avoids any thermal expansion which could affect the accuracy of the measuring process. As it is a non-contact sensor it has no friction or wear.

Despite the fact that this sensor has a very good resolution, it has a very short actual measuring range (22 mm). This short range of the sensors limits its ability to measure edges which are higher or lower than 22 mm. The fact that the sensor is connected to the controller with a fibre optic cable which is only few meters long makes it quite vulnerable to damages and errors for measuring large parts on relatively large machining centres. Furthermore, it requires a thoroughly cleaned and dry work piece for measurement process because it uses the monochromatic light principle for measurement. This problem could be solved by introducing an air flow system in the machining centre to clean the scrap debris off the surface of the part and eventually dry it as well. Since this sensor costs up to 8000€, replacing the sensor due to damages can be very expensive.

3.3. Advantages and Disadvantages of the Laser Triangulation Sensor

This sensor has a fair resolution with the fastest feed rate and measurement frequency of up to 2.5 kHz which enables it to make the measurement processes much faster than those of the mechanical probe and the confocal sensor. It has a very practical actual measurement range (200 mm) and a safe start of measurement range (70 mm). Thus the total range enables it to measure rising or falling edges up to 200 mm of sensor range. This sensor contains membrane keys on top of the sensor itself where it is possible to check the laser state whether it is on or off or whether the sensor is in MR, MMR or out of range as shown in Figure 8. It is also possible to check and change laser sensor's measurement value output, measuring frequency, averaging number, error analogue, averaging type, operation mode, baud rate, and data format from its membrane keys. (9) In addition, it is quite suitable to measure large work pieces on large machining centers in a wide range of industrial processes. The sensor's cable which is few meters long can be connected to a radio transmission system in order to increase its compatibility to work with large machining centers. Furthermore, it has the ability to transmit output signals via the digital interface RS422 output, current output or analog output. The cost of this sensor is about one third of the confocal sensor which makes it quite affordable at a price of around 2700€.

The sensor has a smaller resolution in comparison to the other two measurement systems. Since it is attached to a sensor cable, it limits its ability to work on large machining centers with rotational movements without the integration with a radio transmission. Furthermore, it requires a thoroughly cleaned and dry work environment for measurement processes as it uses laser triangulation principle. By introducing an air flow system in the machining centre, the scrap debris can be cleaned from the surface of the part. Additionally, to measure the surface of metal parts with grinding and rolling marks, the laser plane or laser's angle of deflection has to be adjusted so that it is parallel to the grinding, rolling or polished marks on the surface. Moreover, the sensor requires a warm up time of 20 minutes to achieve a uniform temperature distribution in the sensor. Furthermore, color differences of material to be measured in combination with changes of penetration depth of the laser can also lead to measuring errors. Last but not least, if the work piece being measured is shiny and a low measurement frequency is used, there can be an error in the measurement values due to interference from other light sources. Therefore, shielding is required. (5, 9)

4. Requirements for the Replacement of the Mechanical Inspection Probe

The main requirement for replacing the mechanical inspection probe is that the new optical measurement system must have a faster measuring frequency to that of the mechanical inspection probe. The mechanical inspection probe that is the Renishaw OMP40-2, takes optimum measurements of the surface when it is used at a feed rate of up to 480 mm/min which is 8 mm/sec. The replacement measurement system should not have a limited feed rate. Another critical requirement for the replacement of the mechanical probe is that the accuracy of the optical measurement system for surface detection must be within 100 µm in comparison to the repeatability of the mechanical inspection probe which is 1 µm. Furthermore, the optical measurement system must have at least the same or higher capability of detecting edges in contrast to the mechanical inspection probe. The mechanical inspection probe is unable to measure the true height of the edge which is less than its ball radius (1.5 mm) and it is unable to detect edges longer than its stylus length at all. Additionally, optical measurement systems will require shielding in case of bright environments such as in welding workshops to replace the mechanical probe. Finally, last but not least, optical measurement systems will require thoroughly clean and dry work piece to measure the displacement over its surface. This target can be achieved by introducing an air flow system in the machining center in order to replace a mechanically operated contact probe.

5. Programming and Integration

Both, the confocal chromatic and the laser triangulation measurement systems, were programmed and integrated with a CNC machine to test their reliability, accuracy and precision.

5.1. Integration of Confocal Chromatic Sensor and Laser Triangulation Sensor with a CNC Machine

In order to test the reliability, accuracy and precision of the confocal chromatic sensor and the laser triangulation sensor both were individually integrated with a CNC machine system with a resolution of 25 µm to work as one unified operational unit for measurement process as seen in Figure 10. This target was achieved by individually attaching the optical distance sensors to the tool of the CNC machine and to a computer via RS422 digital interface. Then, a unified program was written for both sensors separately. The coordinates of a position were given to the CNC machine in an input file to move the mounted sensor to a designated location. Subsequently, the laser sensor took the measurement at that coordinate point and stored the position, raw data, displacement and the error inquiry to an output file for analysis at the end of the measurement process. Firstly, both sensors were individually screwed to a metal plate with designated attachment holes drilled in it with minimum offsets of transmitting lenses of each sensor. Consequently, the whole unit was attached to the tool of the CNC machine to initiate the measurement process. Therefore, by using one optical distance sensor at a time it was possible to measure the displacement over the surface of a part by giving multiple coordinate points over the length of the whole part if required. The Z-axis of the CNC machine was not varied during the measurement process as it had a lower resolution of 25 µm in comparison to the higher and better resolution of the confocal chromatic sensor and the laser triangulation sensor, which were 0.9 µm and 12 µm, respectively.

Figure 10 *Integration of the confocal chromatic (left) and the laser triangulation (right) sensors with a CNC machine*

5.2. Coordinate Points Generator

A coordinate point generator was needed to measure a part in the range of microns. Since the smallest step of the CNC machine was 25 µm it was quite problematic because it required a lot of time to generate co-ordinate points manually to cover a wide range of surface area when measuring displacement for each point. For instance, 100 points of 25 micrometer each would actually cover an area which would be 2.5 millimeters long over the surface of the part. In order to overcome such a drag, a point generator program was programmed which required a starting co-ordinate point, an ending co-ordinate point and the increment between these points of the CNC machine. Following, it returned the desired co-ordinates in a list which could be used as an input file for the combined operational program of devices, the sensor and the CNC machine, respectively. This co-ordinate point generator opened the possibility of creating thousands of points automatically in just seconds in contrast to hours in the manual mode.

6. Measurements by means of Integrated Optical Measurement Systems

Measurements of both optical measurement systems that is the confocal chromatic measurement system and the laser triangulation measurement system are carefully taken after integration with a CNC machine and the results are discussed in this chapter.

6.1. Results of the Confocal Chromatic and the Laser Triangulation Sensors

The optical sensors that is the laser triangulation sensor and the confocal chromatic sensor were programmed to measure over the same coordinate points over the same part of the sample surface for comparison. Both sensors were mounted on the tool with the minimum level of offsets of the transmitting lenses. The results of both sensors were quite interesting as shown in Figure 11. After zooming into the displacement of the confocal chromatic sensor over the selected rough surface of the work piece, a line of regression was drawn along with two dotted lines to linearize the surface noise as shown in Figure 12a. It can be clearly seen in this figure that the graphed data contains linear error of approximately ±15 µm with a maximum difference of displacement of approximately 30 µm. Moreover, another line of regression was drawn after zooming into the displacement of the shiny surface shown in Figure 12b. It can be seen in this figure that the linear error of the graphed data is about ±15 µm to ±25 µm with maximum difference in displacement of 50 µm. The linear error could have been caused by the surface roughness, the method or the signal conditioning electronics altogether in case of both kinds of surfaces.

On the other hand, by zooming, it can be seen in Figure 13a that the laser triangulation sensor has a result which contains a maximum difference in displacement of 60 µm over the same selected rough surface which was measured by the confocal chromatic sensor. By drawing the same line of regression which was drawn in Figure 12a and two dotted lines for linearization of the surface noise, it can be seen that the data received from this sensor contains linear error which can be estimated to around ±25 µm. Moreover, it can be seen in Figure 13b that the maximum difference in displacement over the same shiny edge is 150 µm with linear error of about ±50 µm. This linear error could have been caused by the method or the signal conditioning electronics altogether in case of both kinds of surfaces.

This result was quite surprising as the price difference between the two sensors was approximately 3 times the other one. The confocal chromatic sensor cost around 8000€ whereas the laser triangulation sensor cost around 2700€ with a difference in linear error of about ±10 µm for the rough surface and about ±35 µm for the shiny surface between both sensors. Furthermore, the confocal chromatic sensor was unable to measure the height of the part as its measuring range was only 22 mm which was about 10 times lower than the laser triangulation sensor. A 3D-model of the displacement measurement over the surface of the part was also made with the data that was received from the laser triangulation sensor and the coordinate points that were received from the CNC machine as seen in Figure 14 for better understanding and view.

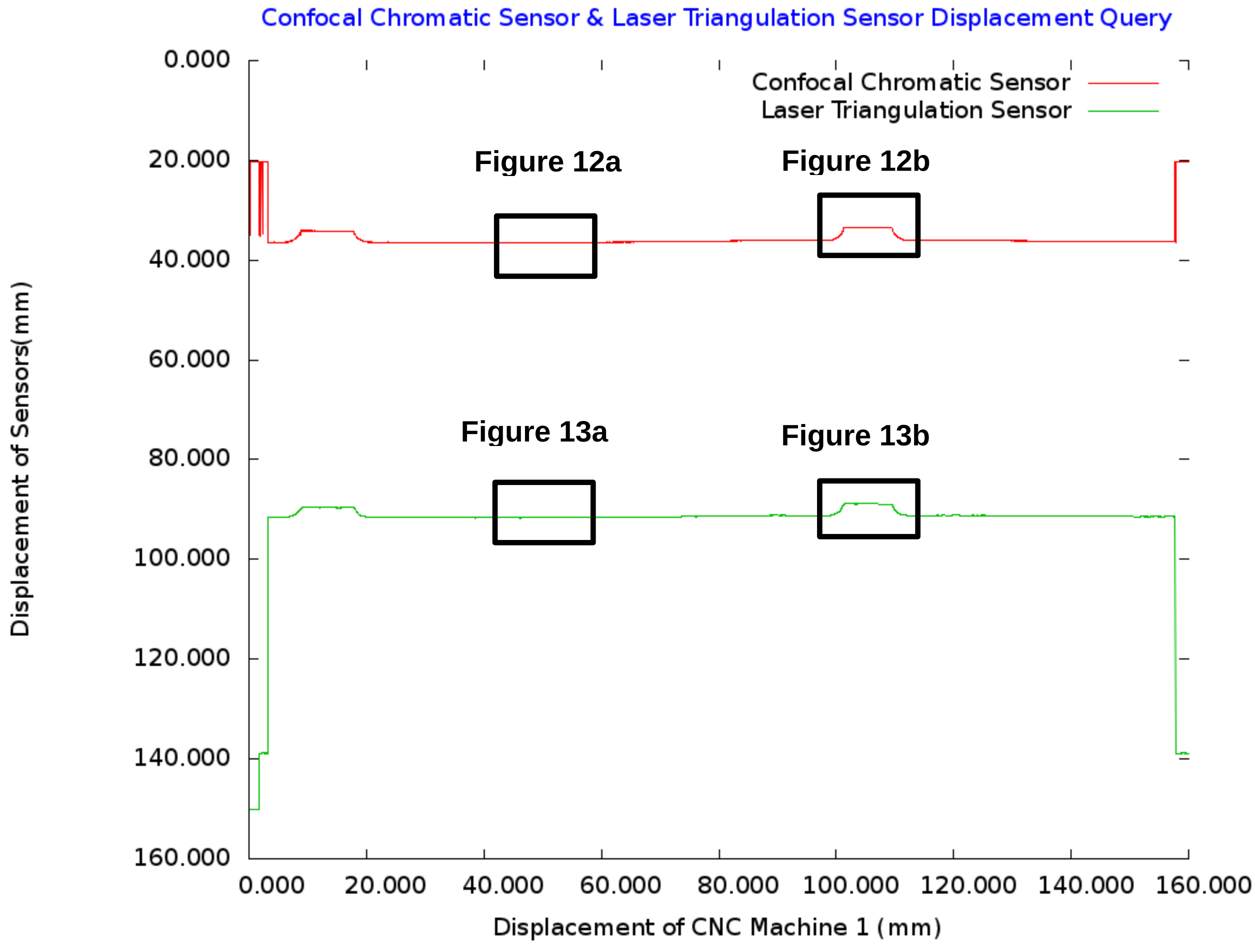


Figure 11 *Confocal chromatic and laser triangulation sensor displacement result*

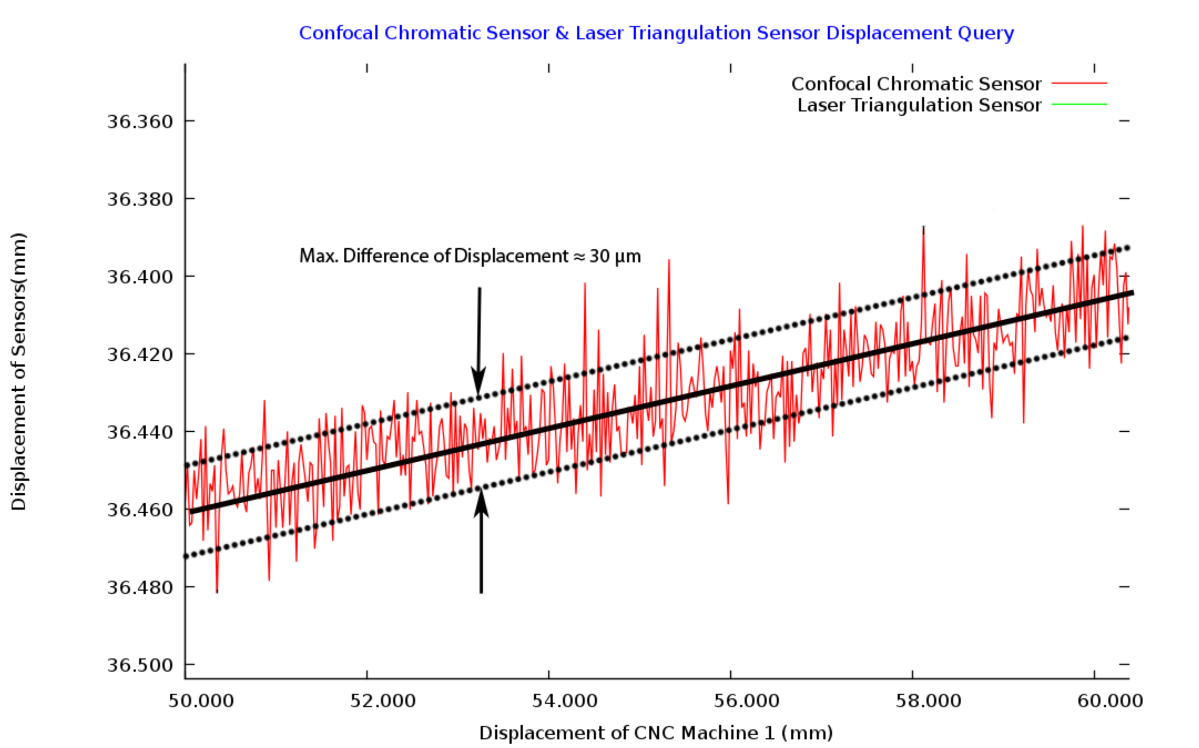


Figure 12a *Result of the confocal chromatic sensor in microns over the grinded surface of the selected part (Max. difference of displacement = 30 µm)*

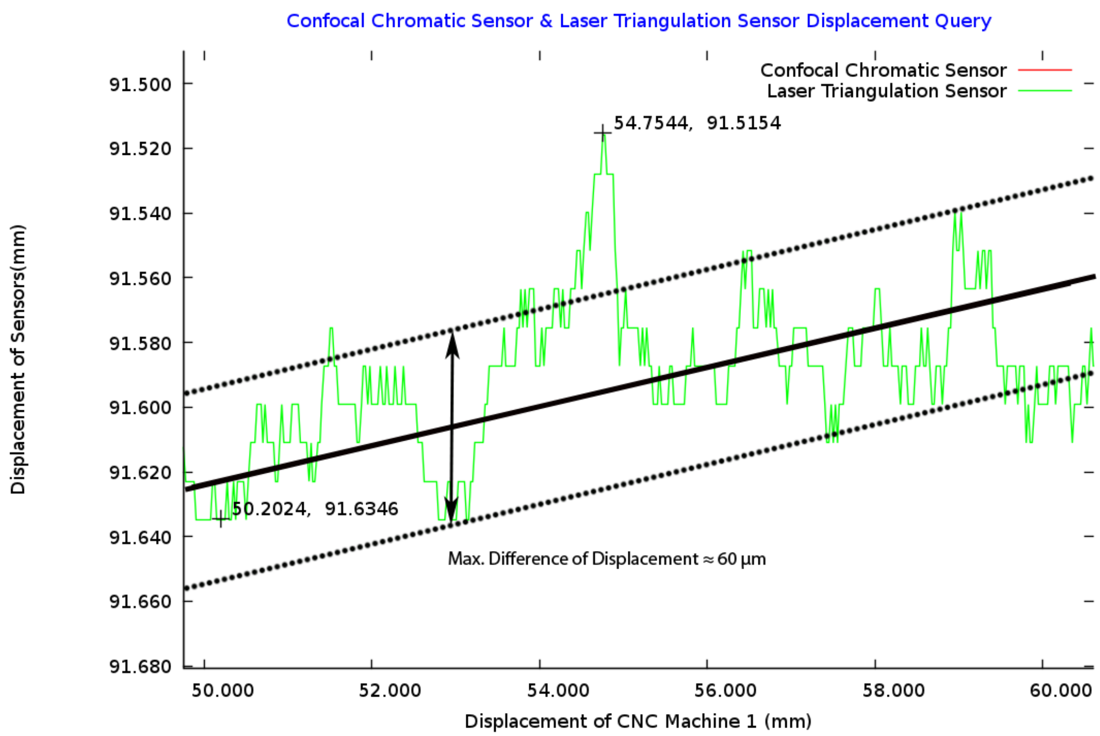


Figure 13a *Result of the laser triangulation sensor in microns over the same grinded surface of the selected part. (Max. difference of displacement = 60 µm)*

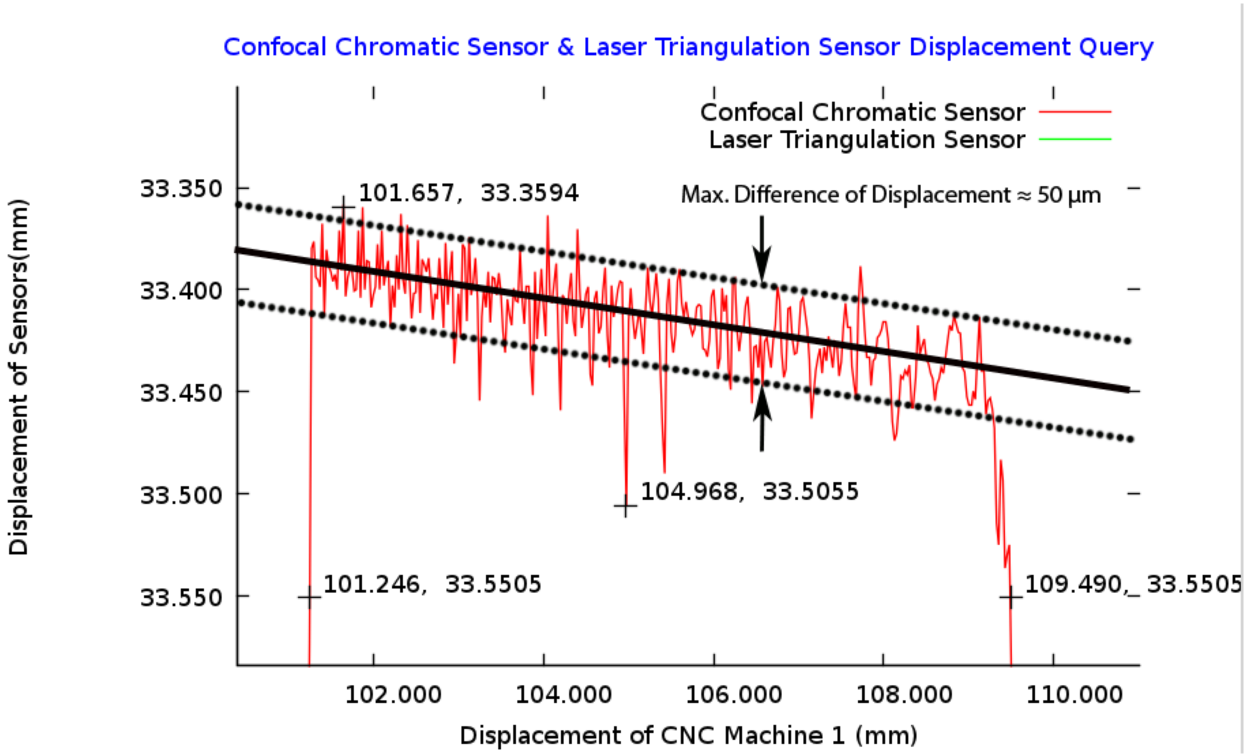


Figure 12b *Result of the confocal chromatic sensor in microns over the shiny polished edge of the selected part (Max. difference of displacement = 50 µm)*

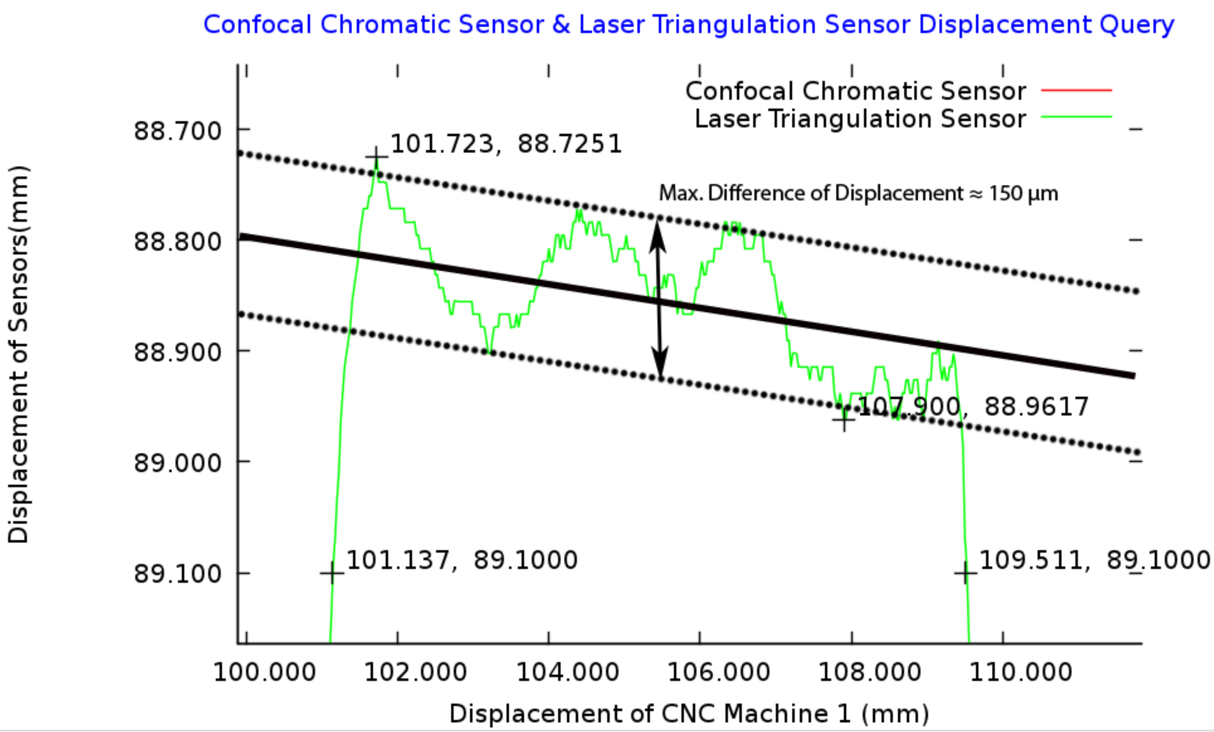


Figure 13b *Result of the laser triangulation sensor in microns over the same shiny polished edge of the selected part (Max. difference in displacement = 150 µm)*

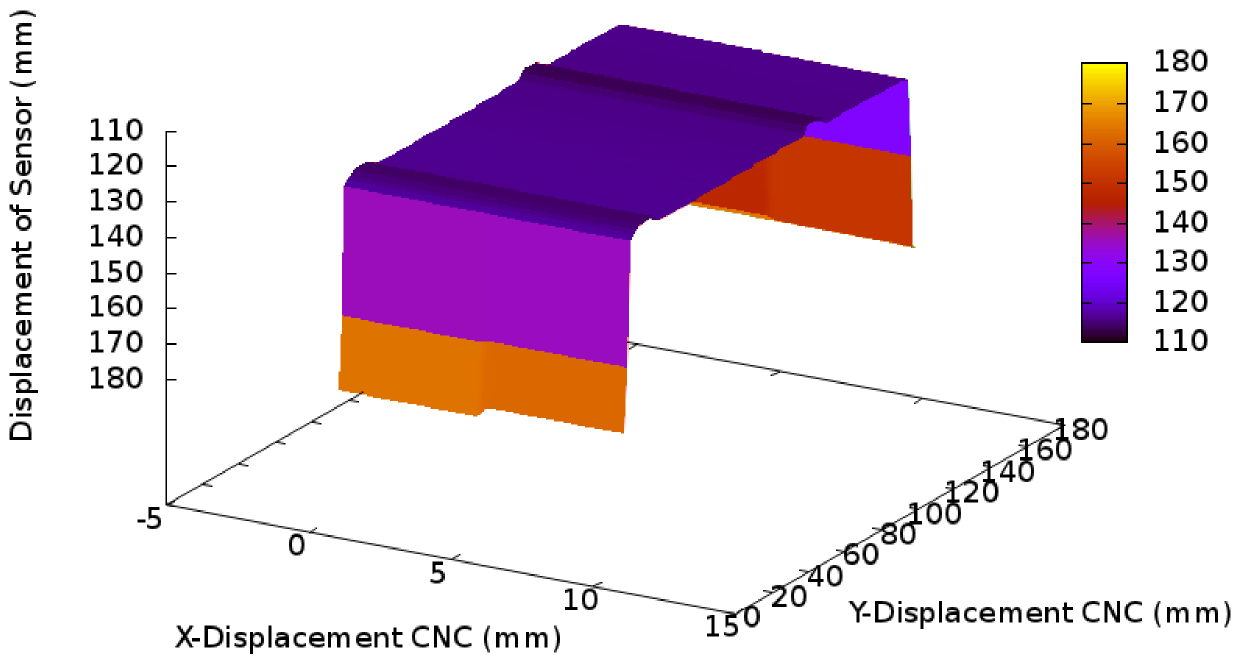
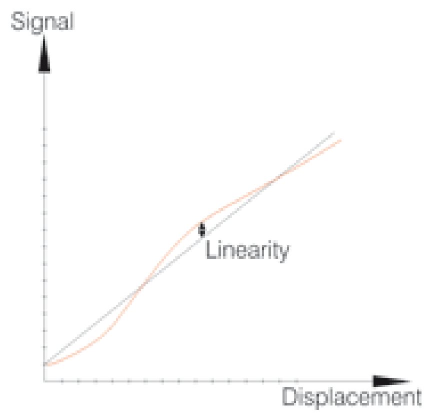


Figure 14 *A three dimensional view of the results received from the laser triangulation sensor*

6.1.1. Calculation of Linear Error

The linearity defines the maximum and minimum values of a measured property. It is the difference between the lowest and the highest measurement points. Graph 1 shows the linearity as percentage of the measurement range. It is used to define accuracy errors. The FSO linear error of both sensors that is the confocal chromatic sensor and the laser triangulation sensor is measured below. (14)



Graph 1 *The % FSO of measurement range (11)*

6.1.1.1. The FSO Linear Error of the Confocal Chromatic Sensor

The FSO linearity of the confocal chromatic sensor is ±0.05 % according to its range (22 mm) in its manual. (10) The theoretical FSO linear error of this sensor can be calculated as following:

FSO: ±0.05 % MR: 22 mm

Linear Error of confocal chromatic sensor:

$$\pm 0.0005 * 22\ mm = \pm 0.011\ mm = \pm 11\ \mu m$$

The total theoretical linear error for confocal chromatic sensor is 22 µm which is quite less than the practically measured linear error which ranges from 30 µm to 50 µm. The increase in error could have been caused by environmental errors such as temperature stability and dust in the air.

6.1.1.2. The FSO Linear Error of the Laser Triangulation Sensor

The FSO linearity of the laser triangulation sensor is ±0.1 % according to its range (200 mm) in its manual. (9) The theoretical FSO linear error of this sensor can be calculated as following:

FSO: ±0.1 % MR: 200 mm

Linear Error of laser triangulation sensor:

$$\pm 0.001 * 200 \text{ mm} = \pm 0.200 \text{ mm} = \pm 200 \text{ µm}$$

The total theoretical range of the sensor is 400 µm which is far greater than the measured linear error which ranges from 60 µm to 150 µm. This could have been caused by stable environmental conditions and a thoroughly clean work piece.

6.2. Comparison of Results with a Vernier Caliper

In order to cross reference the results received from the both optical distance sensors and the CNC machine, measurements of the width of the same edge shown in Figure 12b and Figure 13b were taken with the help of a Vernier caliper which had an error limit of 30 µm (4). The result of this measurement can be seen in Figure 15 below.

Figure 15 *Reading of vernier caliper*

According to this measurement reading the top of the edge is as wide as 8.30 mm. Whereas according to the result of the measurement taken by the confocal chromatic sensor and the CNC machine, the width of the same edge can be calculated with the help of two points marked at the same displacement of the Confocal chromatic sensor in Figure 12b by a simple subtraction as seen below.

$$109.490 - 101.246 = 8.244 \text{ mm}$$

On the other hand according to the result of the measurement taken by the Laser triangulation sensor and the CNC machine, the width of the same edge can be calculated with the help of two points marked at the same displacement of the laser triangulation sensor in Figure 13b by a simple subtraction as seen below.

$$109.511 - 101.137 = 8.374 \text{ mm}$$

The measurement reading of the confocal chromatic sensor deviates from the measurement reading of Vernier Caliper with only 56 micrometers. On the other hand the measurement reading of the laser triangulation sensor differs from the measurement reading of the Vernier Caliper by 74 micrometers. These results illustrate that the measurements taken from all three different measuring devices are quite near to each other therefore proving that they are close to the true value. The deviation in results could have been caused by difference in actual measurement points of the edge by different devices or due to the lower accuracy of the CNC machine or the Vernier caliper used for analysis.

6.3. Conclusion

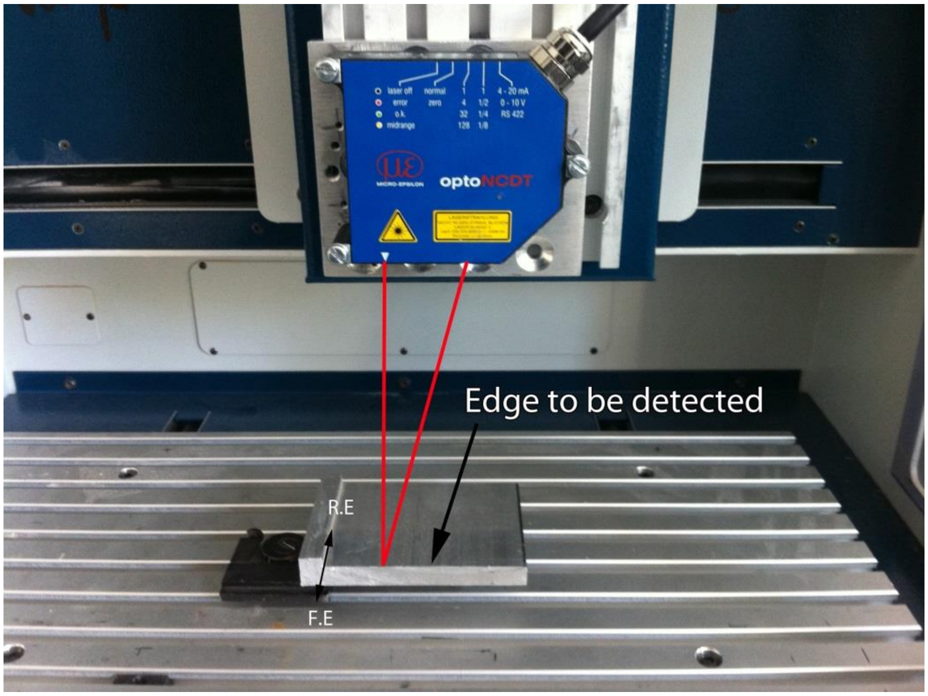
After concluding all the factors shown in Table 1, which include reliability of the sensors, range of the sensors, resolution and measured linear error of the sensors, and cost of the sensors, both sensors that is the confocal chromatic sensor and the laser triangulation sensor did not meet the requirement for replacing the mechanical inspection probe system. The required measurement system for replacement must have a linear error which is at least lower than 100 µm. The confocal chromatic measurement system fulfills this requirement but its measuring range is incompatible of measuring edges of the required parts which are more than 22 mm in height. Therefore, it is disregarded. The laser triangulation sensor has the suitable range for measuring steeper edges however its linearity error is greater than 100 µm. Therefore, the laser triangulation sensor was chosen for further analysis to decrease its linear error if possible and to achieve paramount results for further measuring processes.

Table 1 *Specifications and results of investigated optical sensors*

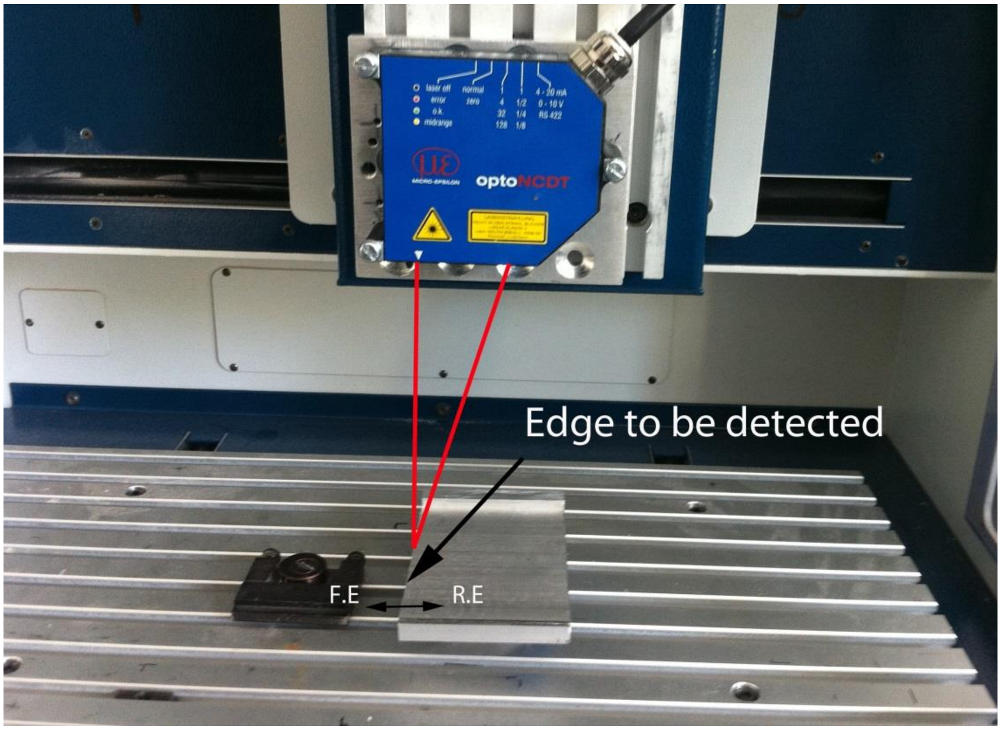
Optical Distance Sensor	**Confocal Chromatic**	**Laser Triangulation**
Measuring Range (mm)	22	200
Start of Measuring Range (mm)	20.2	70
End of Measuring range (mm)	42.2	270
Spot Diameter (µm)	100	1300
Max. Measuring Frequency (kHz)	2.0	2.5
Measuring Capability	Distance Displacement Thickness	Distance Displacement Position Elongation
Transmission Types	Voltage RS232 digital interface RS422 digital interface Universal serial bus	Current Voltage RS422 Digital Interface
Resolution (µm)	0.9	12
Measured Linear Error (≈µm)	30-50	60-150
Approximate Cost (≈€)	8000	2700

7. Laser Triangulation Sensor Edge Detection Analysis with CNC Machine 1

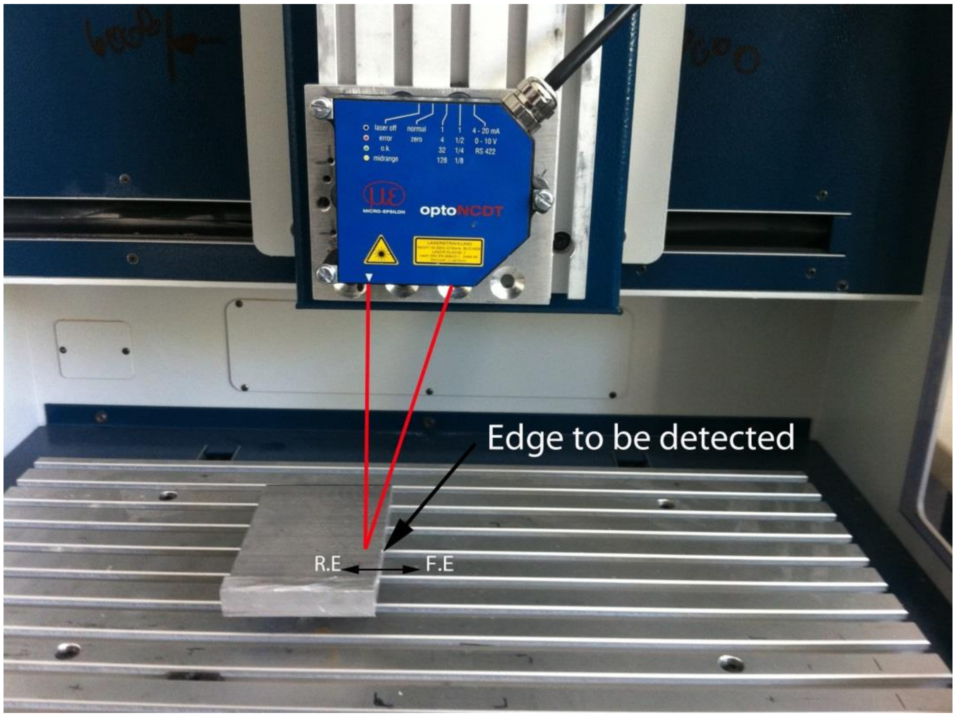
In order to check the proximity of the measurement values to the true value, the accuracy and repeatability of the measurements, the precision of the Laser sensor's edge detection capability three experiments were conducted and repeated up to 100 times by integration with two different CNC machines for concrete results. The first experiment was conducted in such a way that the laser sensor's plane or angle of deflection was parallel to the edge as shown in Sketch 1. Therefore, the laser spot was not obscured by the edge at any point. The second experiment, shown in Sketch 2 was conducted in another way in which the laser sensor's angle of deflection was perpendicular to the edge following that the laser spot was obscured by the edge resulting in blind area of no measurement values. Last but not least, the third experiment was conducted in a final manner in which the laser plane or the laser's angle of deflection was perpendicular to the edge however the laser spot was not obscured by the edge at any point during the measurement cycle as shown in Sketch 3.



Sketch 1 *Experiment 1: Parallel edge detection (R.E: Rising Edge, F.E: Falling Edge)*



Sketch 2 *Experiment 2: Perpendicular edge detection with blind spot (R.E: Rising Edge, F.E: Falling Edge)*



Sketch 3 *Experiment 3: Perpendicular edge detection without blind spot (R.E: Rising Edge, F.E: Falling Edge)*

7.1. Experiment 1 (Parallel Edge Detection) Procedure

As this laser triangulation sensor had already been fully integrated with this CNC machine before it was quite easy to perform the edge detection experiments. This CNC machine consisted of three axes and had an accuracy of 25 µm and it was fully operational according to Chapter 4 of this thesis.

In this experiment, the laser plane or the laser's angle of deflection was parallel to the falling or rising edge that was supposed to be detected resulting in absence of blind spots of the laser at all times during the measurement cycle as shown in Sketch 1 (Pg. 33). This was carried out by moving the laser spot close to the part's rising edge parallel to the laser plane or the laser's angle of deflection and moving it by smallest steps of the CNC machine with each being 25 µm, towards the rising edge and beyond it with an additional 3 steps. Afterwards, the laser spot was moved back towards the falling edge with the same feed rate as well as the same coordinates, and beyond it by an additional 12 steps. This test was carried out 100 times concurrently. The offset of 3 steps after detecting rising edge and the offset of 12 steps for detecting falling edge seemed reasonable for calculating the resolution as well as the precision since the laser sensor was very good at detecting rising edges with the current setup. Only a small part of the laser spot is able to detect the rising edge. However, it needed extra steps in order to notice the falling edge since it was concluded that it held its last measured values in case of small environmental errors.

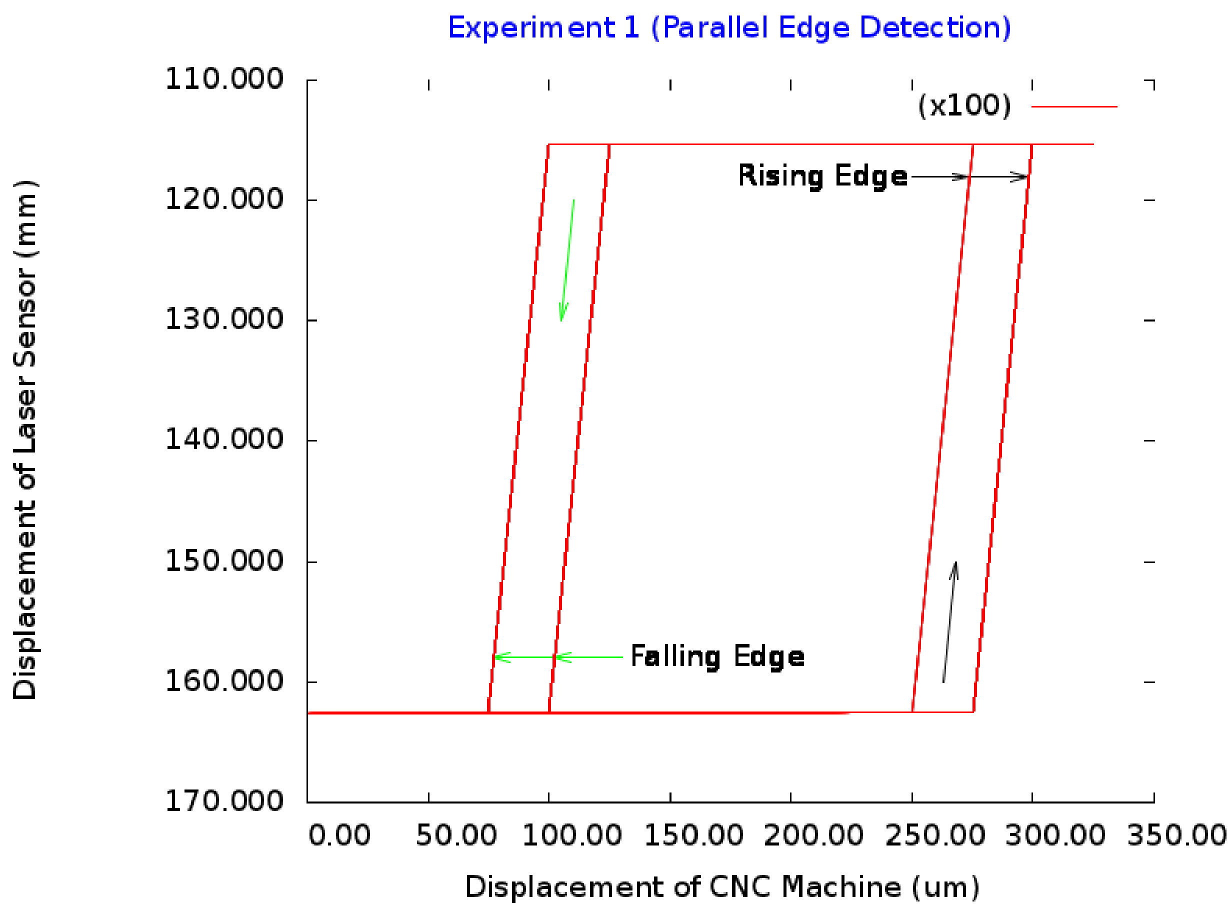


Figure 16 *Result of the parallel edge detection experiment 1*

7.1.1. Results of Experiment 1

In order to completely understand and summarize the results, the data were graphed with the help of Gnuplot seen in Figure 16. The rising edge is detected at 275 µm and 300 µm of displacement of CNC machine over the 100 repeated detections as displacement of the laser sensor is decreased. On the other hand, the falling edge is identified at 75 µm and 100 µm of displacement of the CNC machine over the 100 repeated detections as displacement of the laser sensor is increased. According to this result it can be concluded that the precision of the laser sensor in detecting edges regardless if it is falling or rising deviates up to one step of 25 µm which is the smallest step of the CNC machine used for this experiment. Even though it is quite precise, it could be even more precise if a better CNC machine with a smaller step could be used for the experiment. Furthermore, it was also evaluated that the laser sensor required 150 µm to 200 µm of displacement beyond the falling edge in order to detect it. This is caused by the high sensitivity resolution element such as charged couple device array (CCD) and the fact that the laser spot has a diameter of 1300 µm. Only a small portion of the spot is sufficient enough for CCD element to detect the rising edge whereas the whole laser spot has to be on the bottom of the falling edge in order to complete detect it.

7.1.1.1. Resolution of Rising Edge Detection

In addition, by zooming in to the 2 steps at which the rising edge was detected it can be easily seen in Figure 17 and in Figure 18 that the resolution of the laser sensor for detecting rising edge is between 12 µm to 24 µm, respectively.

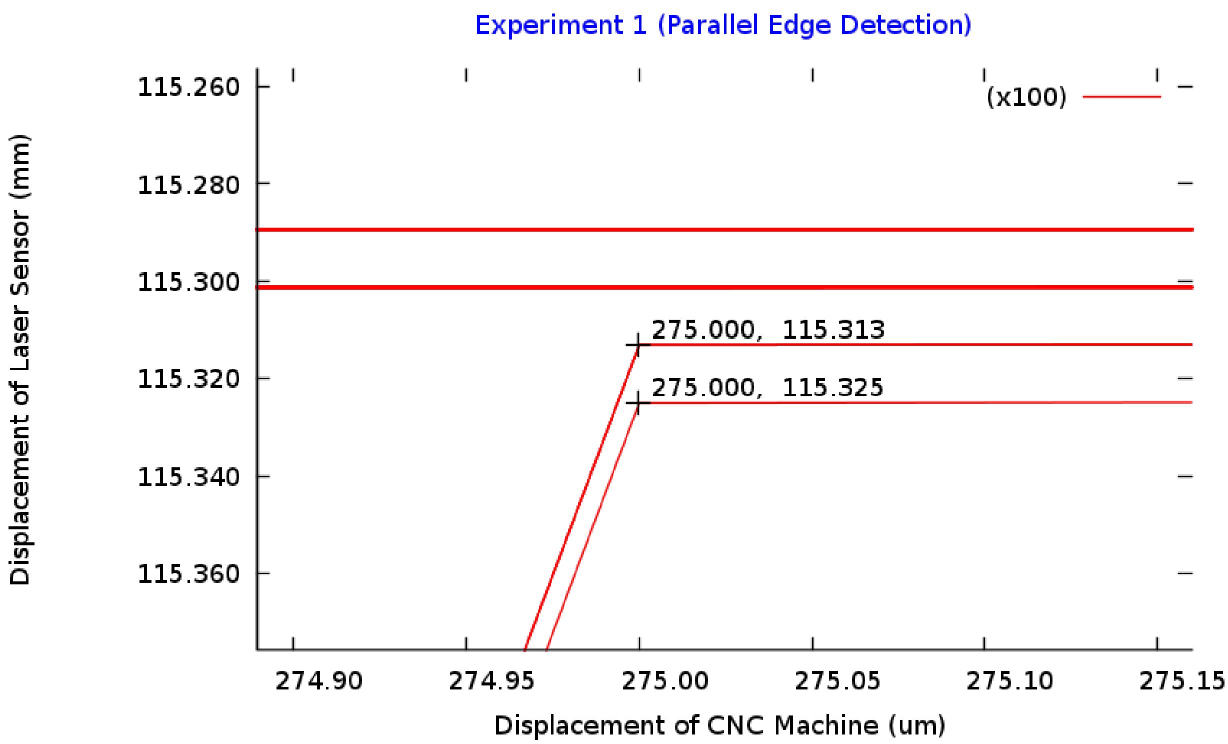


Figure 17 *Resolution of rising parallel edge detection at 250 µm of displacement of CNC machine (12 µm)*

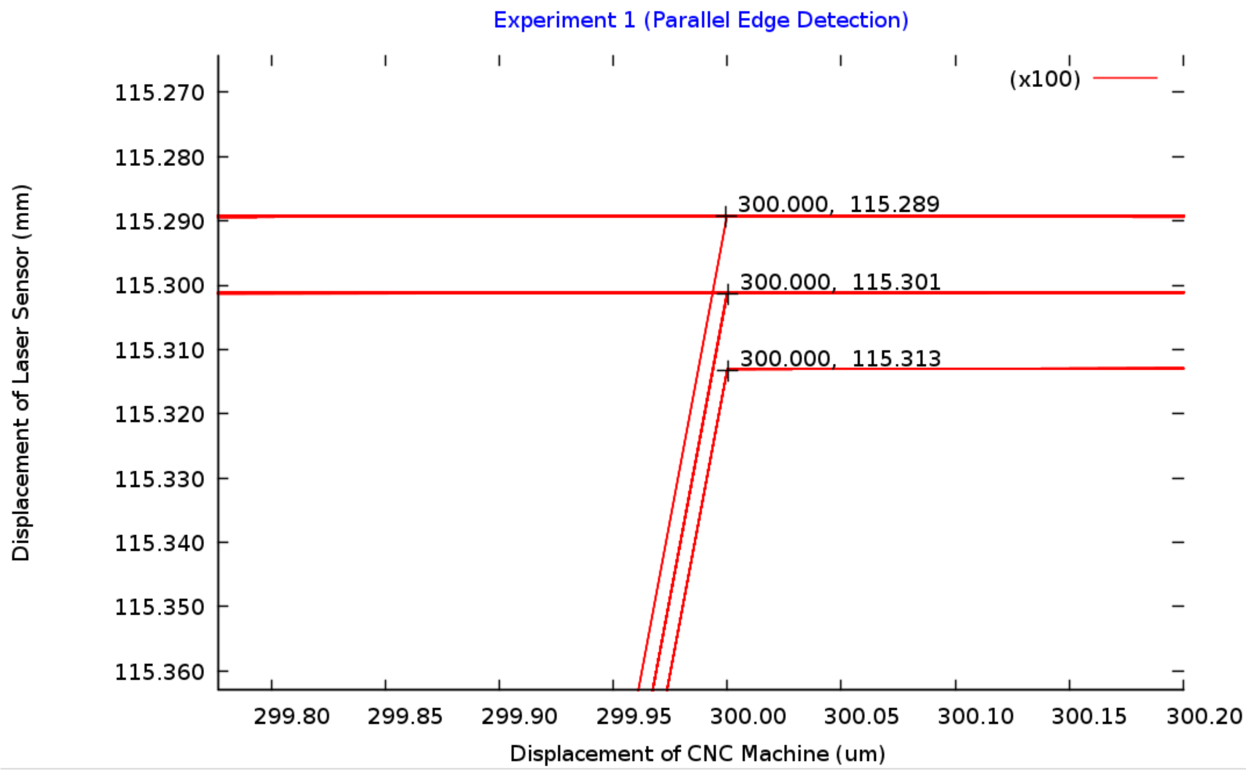


Figure 18 *Resolution of rising parallel edge detection at 300 µm of displacement of CNC machine (24 µm)*

7.1.1.2. Resolution of Falling Edge Detection

Whereas by zooming in to the 2 steps at which the falling edge was detected it can be easily seen in Figure 19 and in Figure 20 that the resolution of the laser sensor for detecting falling edges is between 36 µm to 48 µm, respectively. In contrast, the resolution of falling edge detection was relatively lower than the resolution of rising edge detection. However, both methods of edge detection were very accurate as well as precise in practice.

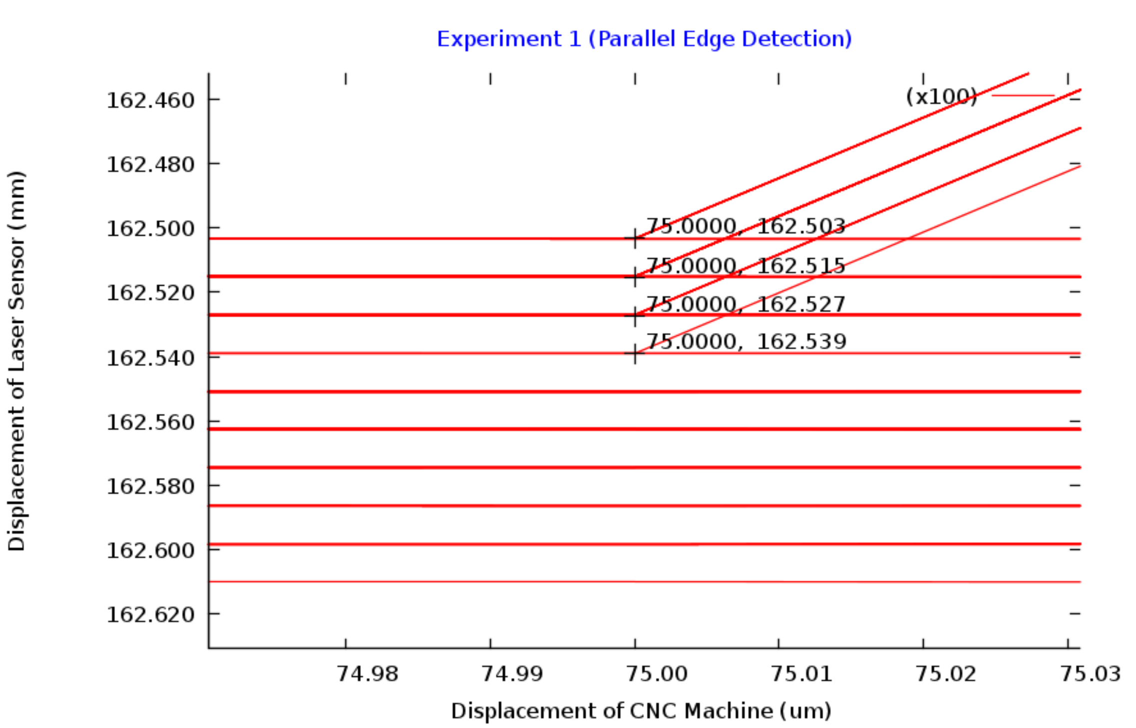


Figure 19 *Resolution of falling parallel edge detection at 75 µm of displacement of CNC machine (36 µm)*

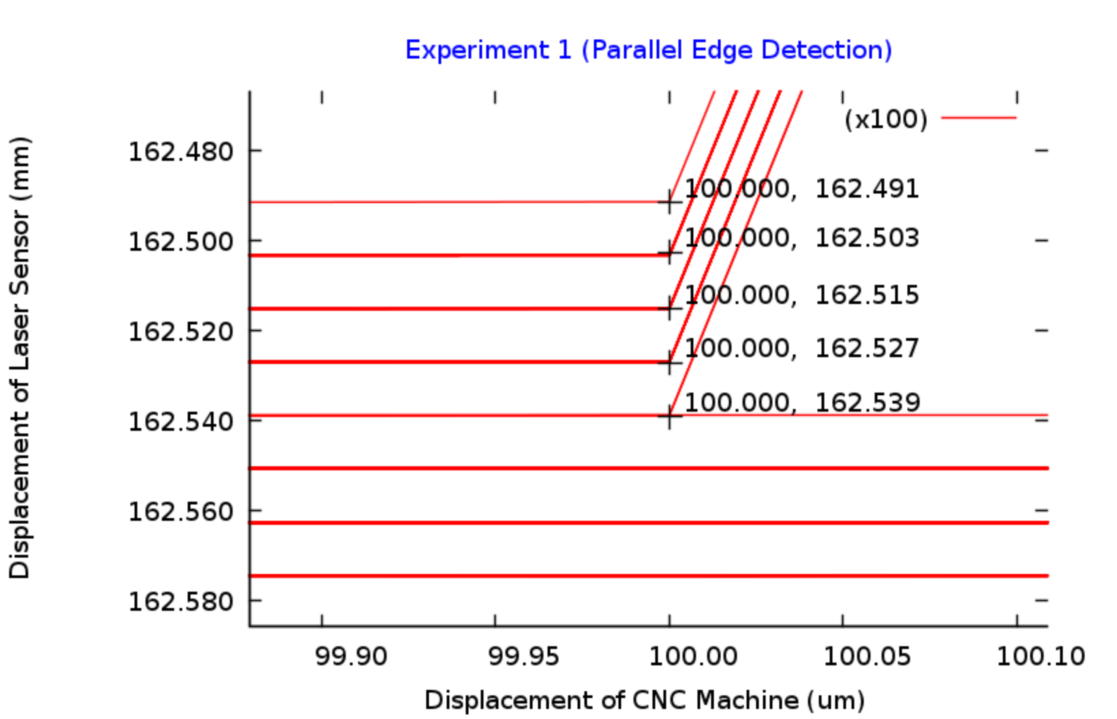


Figure 20 *Resolution of falling parallel edge detection at 100 µm of displacement of the CNC machine (48 µm)*

7.2. Experiment 2 (Perpendicular Edge Detection with Blind spot) Procedure

While performing this experiment, the laser plane or the laser’s angle of deflection was perpendicular to the falling or rising edge that was supposed to be detected as shown in Sketch 2 (Pg. 34). A blind spot was formed as the laser plane or laser’s angle of deflection went off the falling edge thus transferring measurement values of zero. The laser sensor produced actual measurement values only when the rising edge had been detected. This was carried out by moving the laser spot close to the part’s rising edge perpendicular to the laser plane or the laser’s angle of deflection and moving it by smallest steps of the CNC machine used with an accuracy of 25 µm, towards the rising edge and beyond it with an additional 7 steps. Afterwards, the laser spot was moved back towards the falling edge with the same feed rate as well as the same coordinates, and beyond it by an additional 7 steps. This test was carried out 100 times simultaneously. The offsets of 7 steps after detecting rising or falling edge seemed reasonable as less precision was expected.

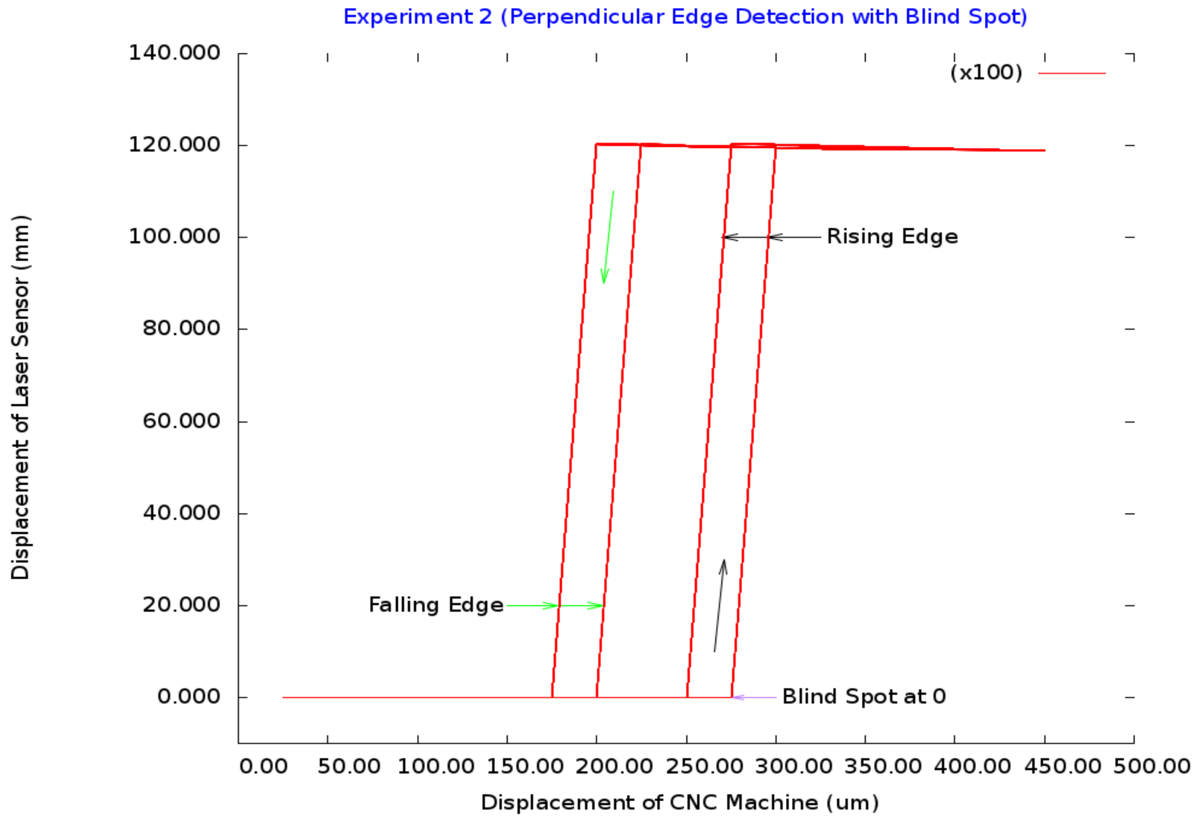


Figure 21 *Result of perpendicular edge detection experiment 2*

7.2.1. Results of Experiment 2

In order to summarize the results received from this experiment, the data were graphed with the help of Gnuplot seen in Figure 21. In this case, the rising edge is detected at 275 µm and 300 µm of displacement of the CNC machine over the 100 repeated detections as displacement of the laser sensor is increased. On the other hand, the falling edge is detected at 175 µm and 200 µm of displacement of the CNC machine over the 100 repeated detections as displacement of the laser sensor reaches zero. From this result, it concluded that the precision of laser sensor for detecting rising edge and falling edge deviates up to 25 µm which is as high as the resolution of the CNC machine used for the experiment. Therefore, the precision of the laser sensor is the same when measuring edges with the laser plane or the laser's angle of deflection being perpendicular to the edge of the part with a blind spot in contrast to the laser plane or laser's angle of deflection being parallel to the edge with no blind spot.

However, no values of the falling edge are detected due to the blind spot. Lastly, the laser sensor detected the blind spot or the falling edge and the rising edge within 50 µm to 100 µm of gap in between them due to the high sensitivity element of CCD.

7.2.1.1. Resolution of Rising Edge Detection

By zooming in to the 2 steps at which the rising edge was detected it can be easily seen in Figure 22 and in Figure 23 that the resolution of the laser sensor for detecting rising edge is between 135 µm and 208 µm, respectively. Therefore, it can be concluded that the resolution of the laser sensor is much lower when detecting rising edge while laser plane or laser's angle of deflection is perpendicular to the edge of the part with blind spots rather than parallel without any blind spots.

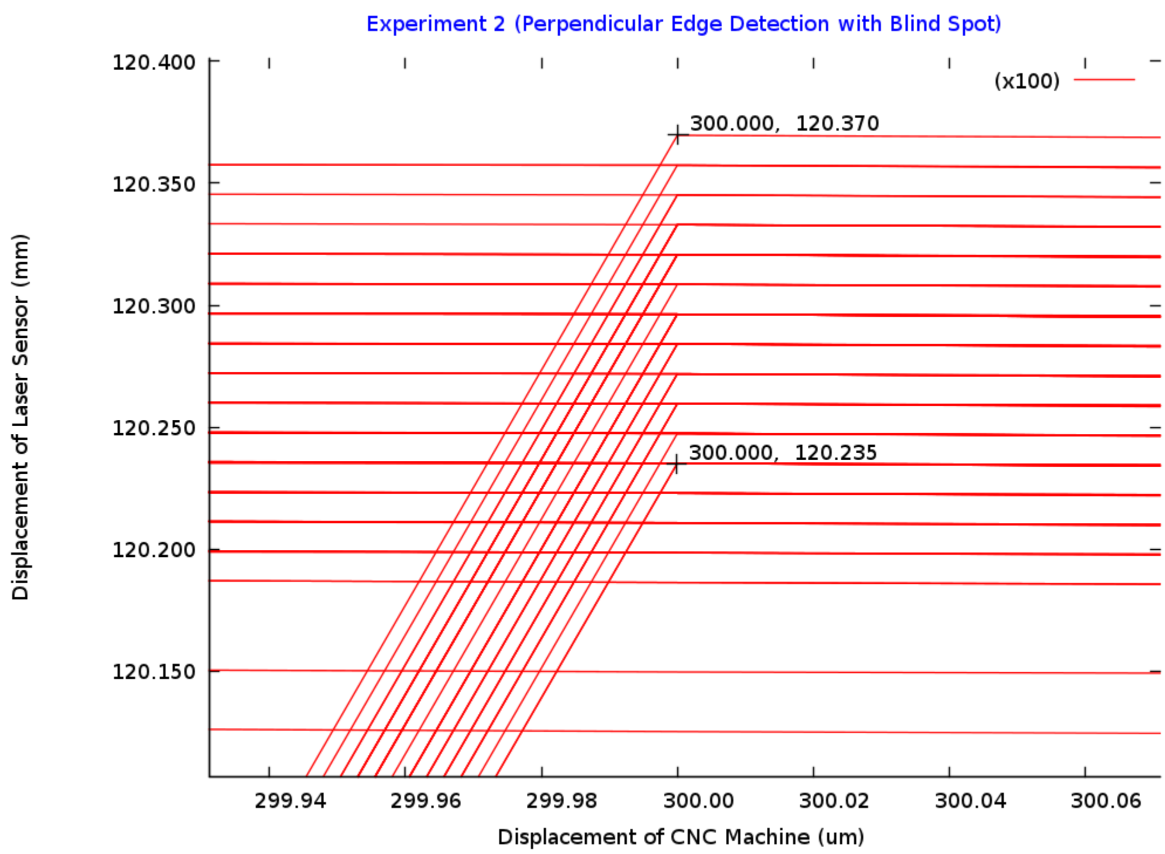


Figure 22 *Resolution of rising edge detection at 300 µm of displacement of the CNC machine (135 µm)*

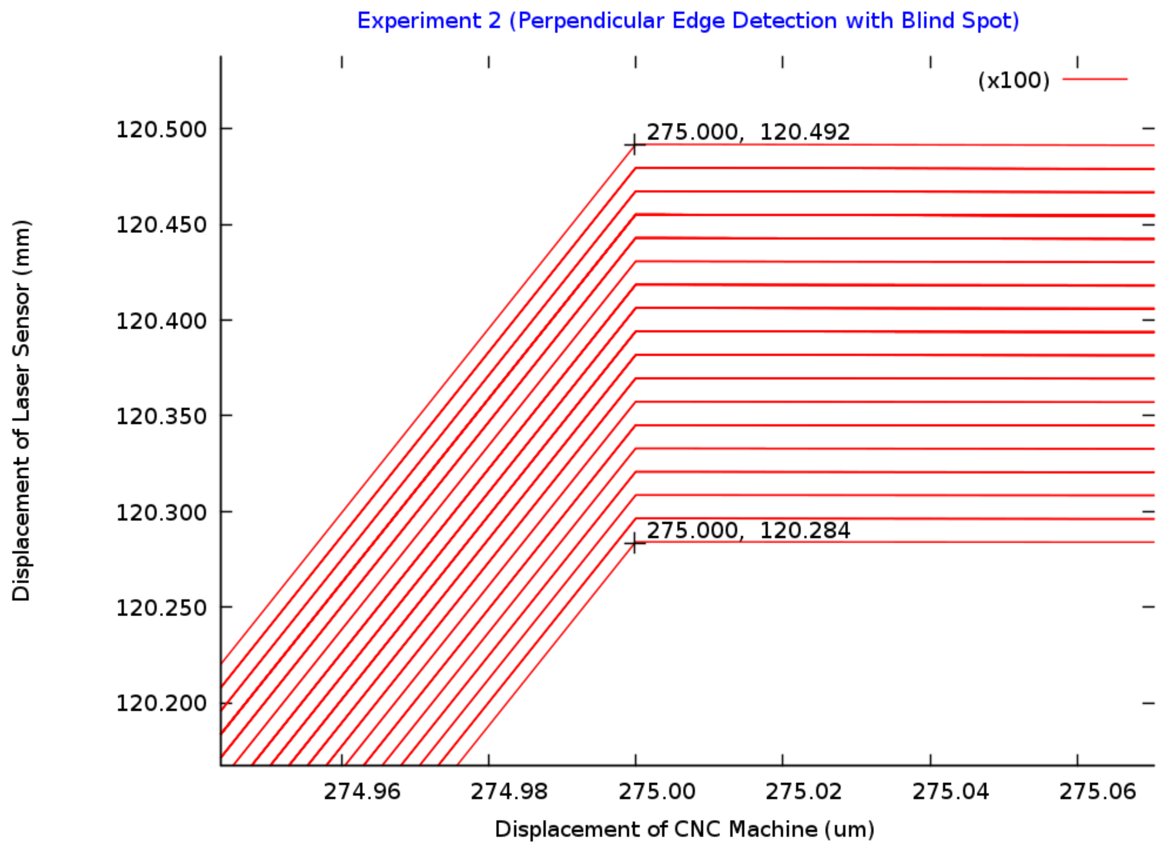


Figure 23 *Resolution of rising edge detection at 275 µm of displacement of the CNC machine (208 µm)*

7.2.1.2. Resolution of Falling Edge Detection

On the other hand, by zooming in to the 2 steps at which the falling edge caused by blind spot was detected, it can be easily seen in Figure 24 that the resolution of the laser sensor while detecting falling edge is exactly 0 in each case since no measurement is issued at this incident. However, the resolution of 2 steps, just before the blind spot was detected is 256 µm and 209 µm as seen in Figure 25 and in Figure 26, respectively. Therefore, it can be concluded that the resolution of the laser sensor is much lower when measuring a falling edge when laser plane or laser's angle of deflection is perpendicular with blind spots in contrast to when it is parallel without any blind spots to the edge of the part that is to be measured.

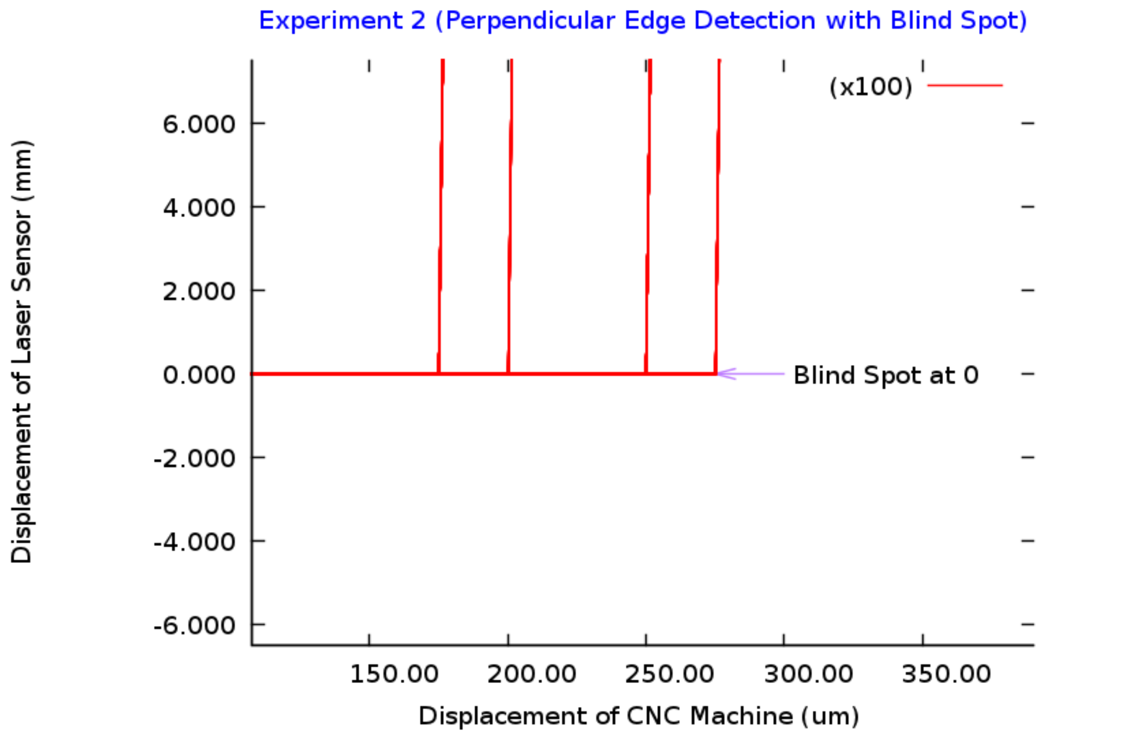


Figure 24 *Blind spot detected by the laser sensor*

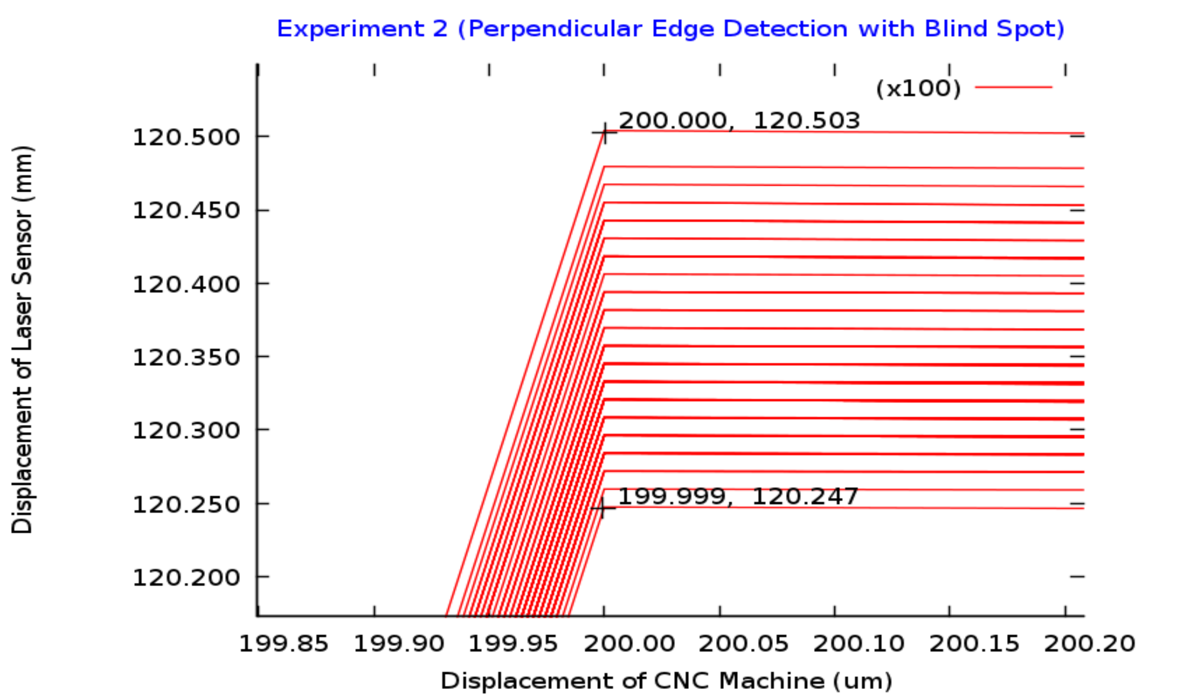


Figure 25 *Resolution of falling edge detection at 200 µm of displacement of the CNC machine (256 µm)*

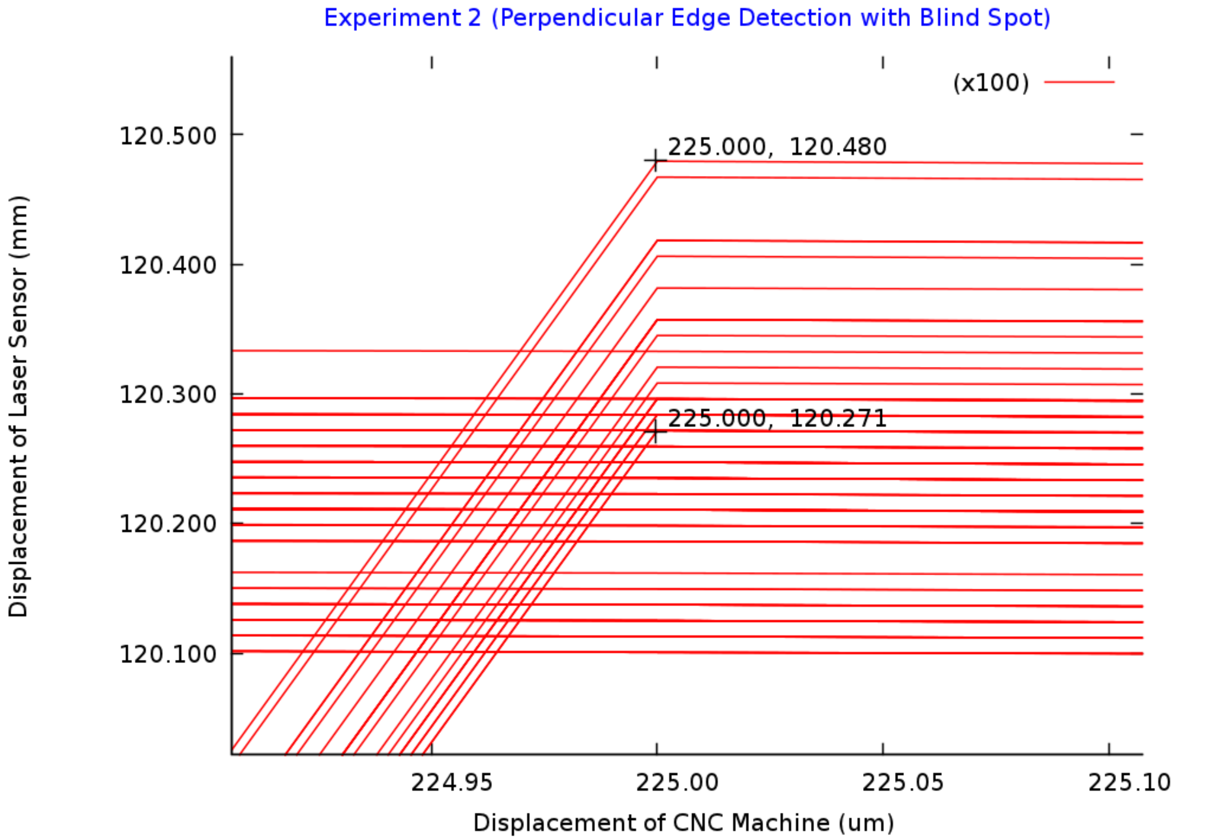


Figure 26 *Resolution of falling edge detection at 225 µm of displacement of the CNC machine (209 µm)*

7.3. Experiment 3 (Perpendicular Edge Detection without Blind spot) Procedure

This experiment was conducted by following the same principle used in the second experiment except the fact that there was no blind spot of the laser while the laser plane or the laser's angle of deflection was perpendicular to detect rising edge or falling edge as shown in Sketch 3 (Pg. 33). There was no blind spot of the laser since the device was set in such a manner that the laser's angle of deflection was away from the rising edge rather than towards the rising edge followed in experiment two. This was carried out by moving the laser spot close to the part's rising edge perpendicular to the laser plane or the laser's angle of deflection and moving it by smallest steps of the same CNC machine used in experiment 1 and 2 with an accuracy of 25 µm, towards the rising edge and beyond it with additional 7 steps. Afterwards, the laser spot was moved back towards the falling edge with the same feed rate as well as the same coordinates, and beyond it by additional 7 steps. This test was carried out 100 times concurrently. The offset of 7 steps after detection was the same as in experiment two since lower precision was expected.

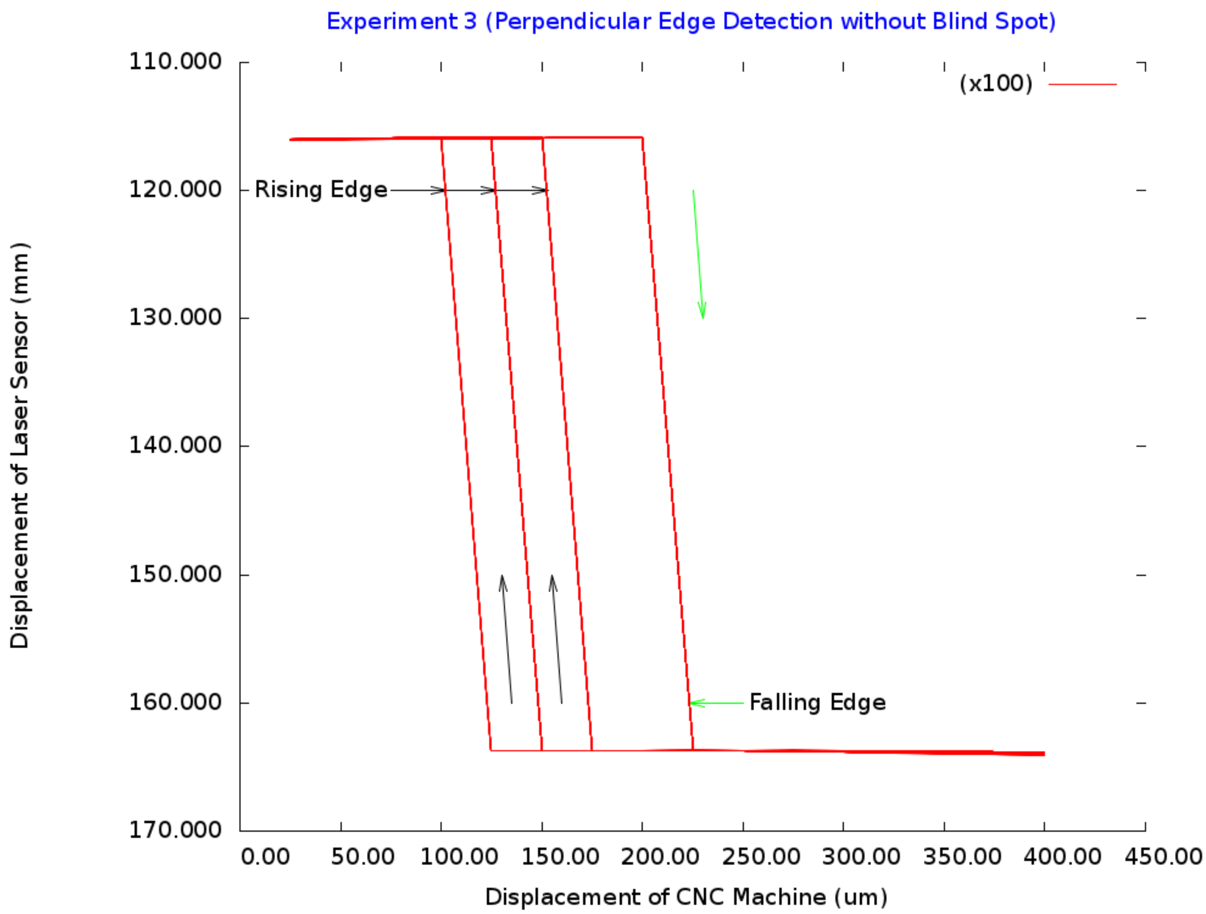


Figure 27 *Result of perpendicular edge detection experiment 3*

7.3.1. Results of Experiment 3

In order to completely summarize the results of this experiment, the data were plotted with the help of Gnuplot shown in Figure 27. The rising edge is detected at a displacement of 100 µm, 125 µm and 150 µm of the CNC machine over the 100 repeated detections as displacement of the laser sensor is decreased. While coming back, the falling edge is only detected at a displacement of 225 µm of the CNC machine over the 100 repeated detections as displacement of the laser sensor is increased. According to this result, the rising edge is detected within 50 µm and the falling edge is always detected at the same coordinate point or the same displacement of the CNC machine used for the experiment. The falling edge detection is as precise as possible with the current CNC machine thus the most precise in all experiments. However, the rising edge detection's precision is lower than in Experiment 1 and in Experiment 2. Nevertheless, it is still quite precise in practise. Furthermore, it was evaluated from the Figure 27 that the laser sensor required 50 µm to 100 µm gap of displacement of CNC machine between the rising edge and the falling edge in order to detect both due to the high sensitivity of the CCD. Only a small portion of the laser spot is sufficient enough for CCD element to detect the rising edge while the whole laser spot has to be on the bottom of the falling edge in order to complete detect it. Therefore, the gap could have been caused by the lower resolution of the CNC machine used for the experiment.

7.3.1.1. Resolution of Rising Edge Detection

In addition, by zooming into the three steps at which the rising edge was detected it can be easily seen in Figure 28, Figure 29 and Figure 30 that the resolution of the laser sensor while detecting rising edge is 12 µm, 48 µm, and 24 µm, respectively, which is nearly same as in experiment 1 with a difference 12 µm and much higher than in Experiment 2.

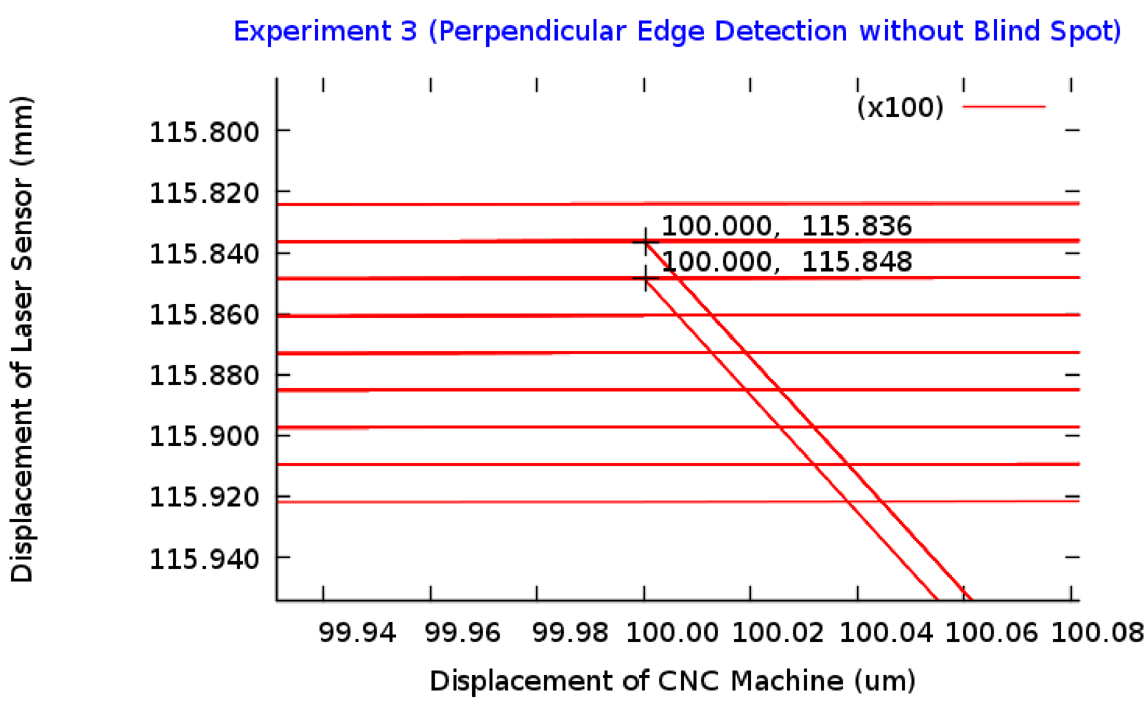


Figure 28 *Resolution of rising edge detection at 100 µm of displacement of the CNC machine (12 µm)*

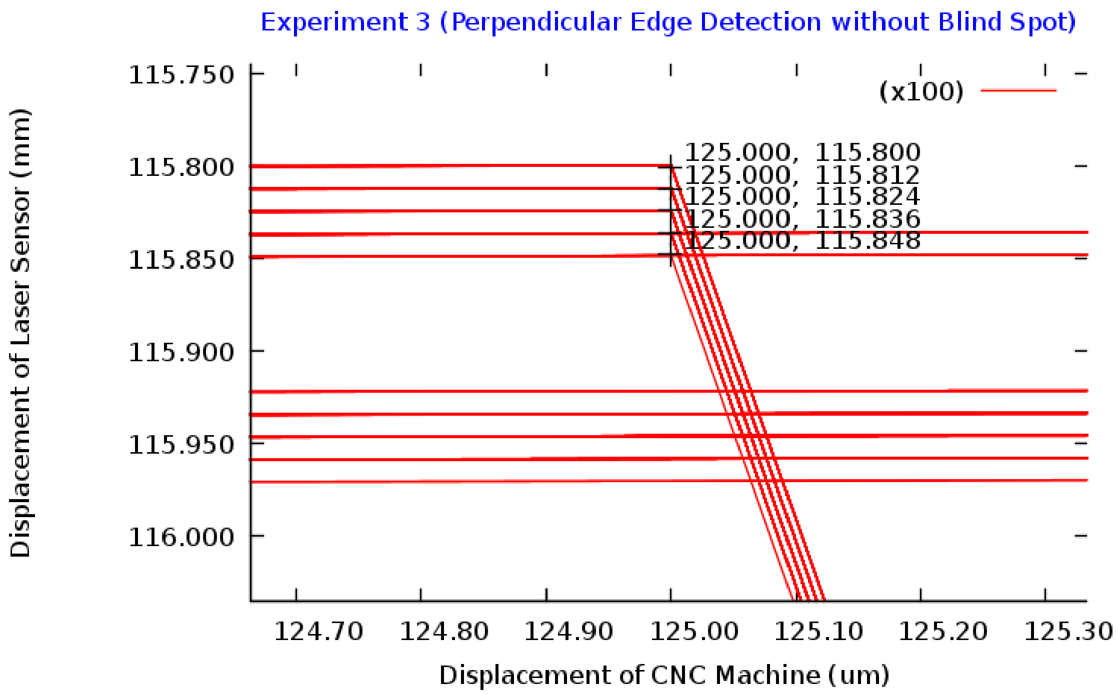


Figure 29 *Resolution of rising edge detection at 125 µm of displacement of the CNC machine (48 µm)*

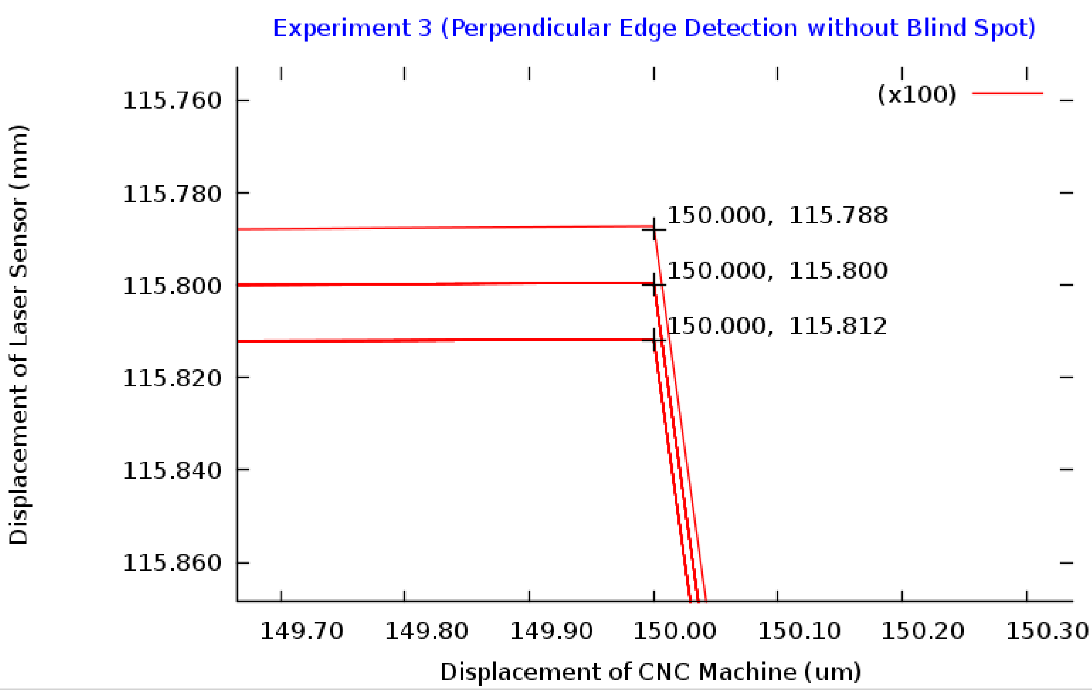


Figure 30 *Resolution of rising edge detection at 150 µm of displacement of the CNC machine (24 µm)*

7.3.1.2. Resolution of Falling Edge Detection

On the other hand, by zooming in to the single step at which the falling edge was detected it can be seen in Figure 31 that the resolution of the laser sensor while detecting falling edge is 62 µm. This result determines that the resolution of falling edge is better than the setup of experiment 2 however lower than in experiment one with a difference of 14 µm.

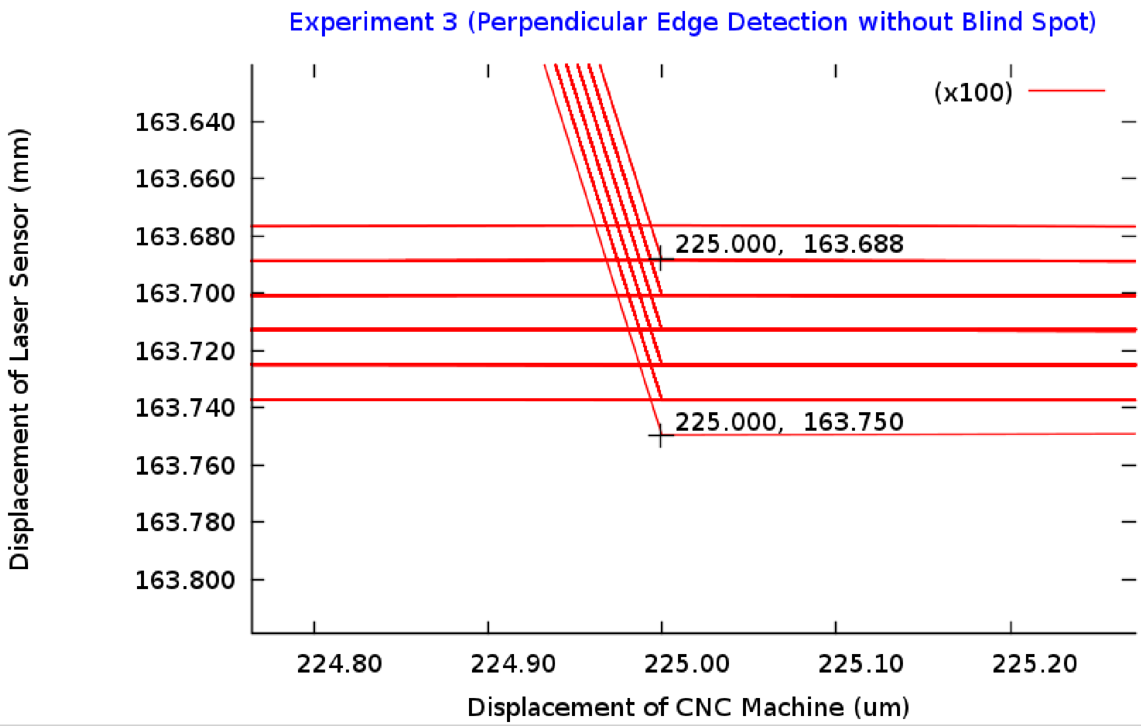
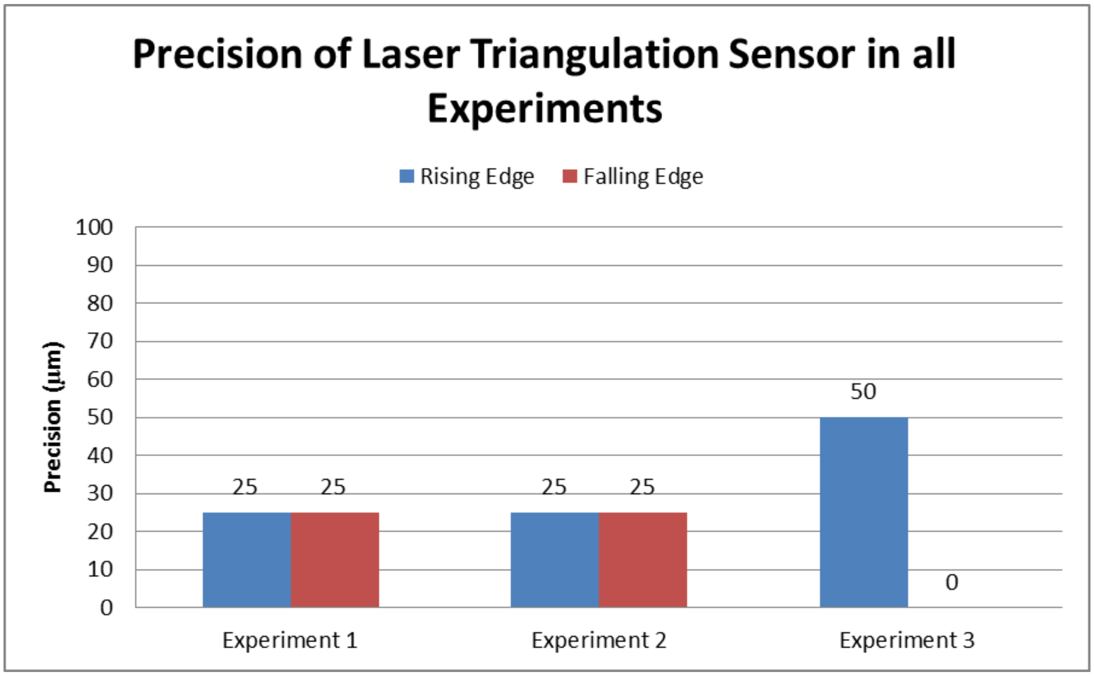


Figure 31 *Resolution of falling edge detection at 225 µm of displacement of the CNC machine (62 µm)*

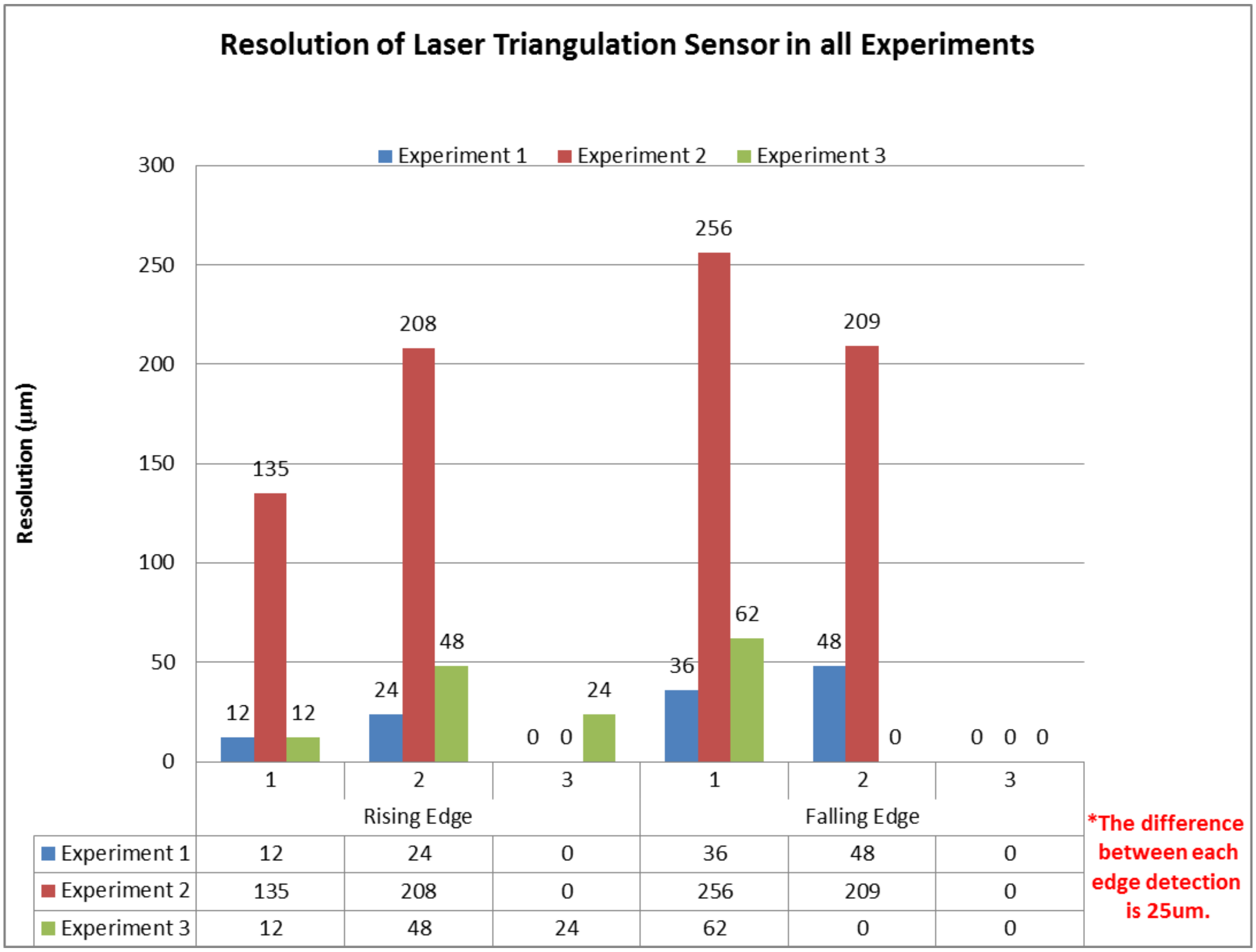
7.4. Edge Detection Conclusion (CNC Machine 1)

According to the results of the three experiments conducted above Graph 2 and Graph 3 were plotted using Microsoft Excel for further analysis. According to the graphs, it can be easily seen that the laser sensor in experiment 1 experienced the same level of precision as in experiment 2 but qualified for the highest level of resolution in contrast to experiment 2 and to experiment 3. The laser sensor provided the lowest level of resolution in experiment 2. In addition, it showed the highest level of precision in detecting falling edge in experiment 3, however at the same time presenting the lowest level of precision for detecting rising edges compared to other two experiments. The resolution of laser sensor in experiment 3 was greater than in experiment 2 however still quite relatively lower than in experiment 1.

In conclusion, the setup in Experiment 1 when the laser plane or laser's angle of deflection is parallel to the edge of the part to be measured is the best choice for detecting rising edges as well as detecting falling edges since it qualified for the highest level of precision along with highest level of resolution of the laser triangulation sensor.



Graph 2 *Precision of the laser triangulation sensor in all experiments conducted with the CNC machine 1*



Graph 3 *Resolution of the laser triangulation sensor in all experiments conducted with the CNC machine 1*

8. Laser Triangulation Sensor Edge Detection Analysis with CNC Machine 2

In order to further analyze the edge detection of the laser triangulation sensor, it was investigated and tested with another CNC machine. Similar experiments to those performed with the CNC machine 1 were conducted. Sketch 4 shows the laser triangulation sensor attached to the tool of the CNC machine. This multi axis CNC machine consisted of 5 axes and had theoretical accuracy of 1 µm which was 25 times better than the CNC machine 1 used in previous experiments. However, due to lack of time the laser triangulation sensor was not completely integrated with this CNC machine. Therefore, the coordinate points of the CNC machine and the measurement values of the laser sensor were not synchronized automatically. These had to be operated and recorded manually for each step. Consequently, the number of measurement points for each edge detection experiment was reduced to 50 points and were repeated up to three times. Furthermore, as this CNC machine was much larger than the CNC Machine 1 and had the ability to rotate as well, the laser triangulation sensor was upgraded with a radio transmission system. Additionally, it was also equipped with rechargeable batteries to power it. This upgrade eliminated its wiring for power and data transfer to a computer. The other end of the radio transmission was connected to a field programmable gate array (FPGA) which transmitted data to a computer in transparent mode.

Sketch 4 *Laser triangulation sensor attached to the tool of the CNC machine 2*

8.1. Experiment 1 (Parallel Edge Detection) Procedure

During this experiment, the laser plane or the laser's angle of deflection was parallel to the falling or rising edge that was to be detected. Therefore, there was no presence of blind spot of the laser at all times during the measurement cycle as it was shown in Sketch 1 (Pg. 33). Firstly, the whole unit consisting of the laser triangulation sensor, its battery and its radio transmission along with its antenna was attached to the tool of the CNC machine and the work piece was placed and clamped in the machine's working area. Then the laser triangulation sensor was moved to such a position in the Z axis that its middle of measuring range (MMR) represented by a yellow LED on the sensor was at top of the surface of the work piece. Afterwards, the laser spot was taken of the edge by moving it in steps of 1 µm each. As the MMR yellow LED was changed to green representing change in displacement, the position was marked as the reference point of the experiment. After that the laser sensor was moved towards the rising edge and beyond it by 200 µm in an increasing series of steps. The first 10 µm were covered by steps of 1 µm each, following by steps of 10 µm each up to 100 µm and finally by steps of 20 µm each until 200 µm. Then it was moved to the reference point and beyond it in the same increasing series of steps until 200 µm. The measurement value for each point was recorded manually on a piece of paper from the computer which was attached to the FPGA. This measurement cycle was repeated up to 3 times. Finally, the data from measurement values were typed in a computer and were graphed with the help of Gnuplot seen in Figure 32.

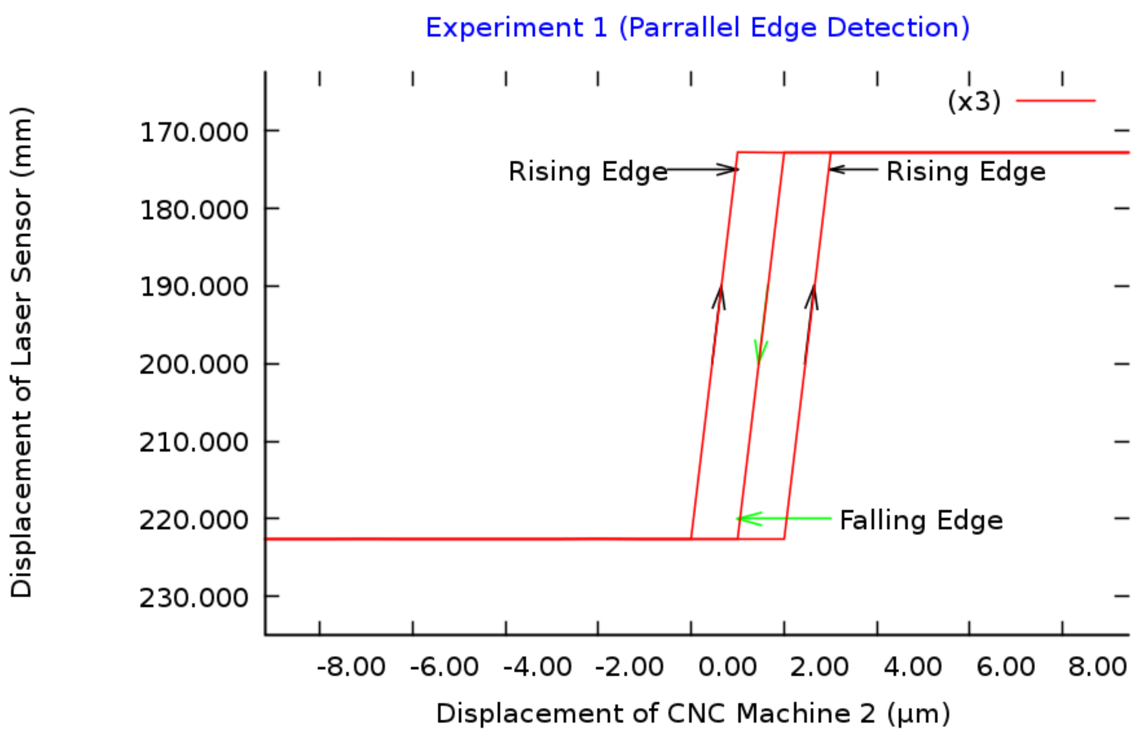


Figure 32 *Result of parallel edge detection with CNC machine 2*

8.1.1. Results of Experiment 1

It can be seen from Figure 32 that the result looks very accurate as well as precise. The rising edge is detected at displacement of 1 µm and 3 µm of the CNC machine over the three repeated detection as the displacement of the laser sensor is decreased. The falling edge is detected at displacement of 1 µm of the CNC machine over the 3 repeated detections as the displacement of laser sensor is increased. The rising edge is detected within 2 µm of displacement of the CNC machine and the falling edge is detected at the same coordinate point or the displacement of the CNC machine. According to these results the precision of the laser sensor is incredibly precise. This is almost the same as the resolution of the CNC machine which is used for this experiment.

8.1.1.1. Resolution of Rising Edge detection

By zooming into the two steps at which the rising edge was detected the resolution of detecting rising edge of the laser triangulation sensor is 13 µm as it can be seen in Figure 33. This resolution is almost the same as the resolution of the laser sensor therefore it is the optimal result that can be received from this laser sensor.

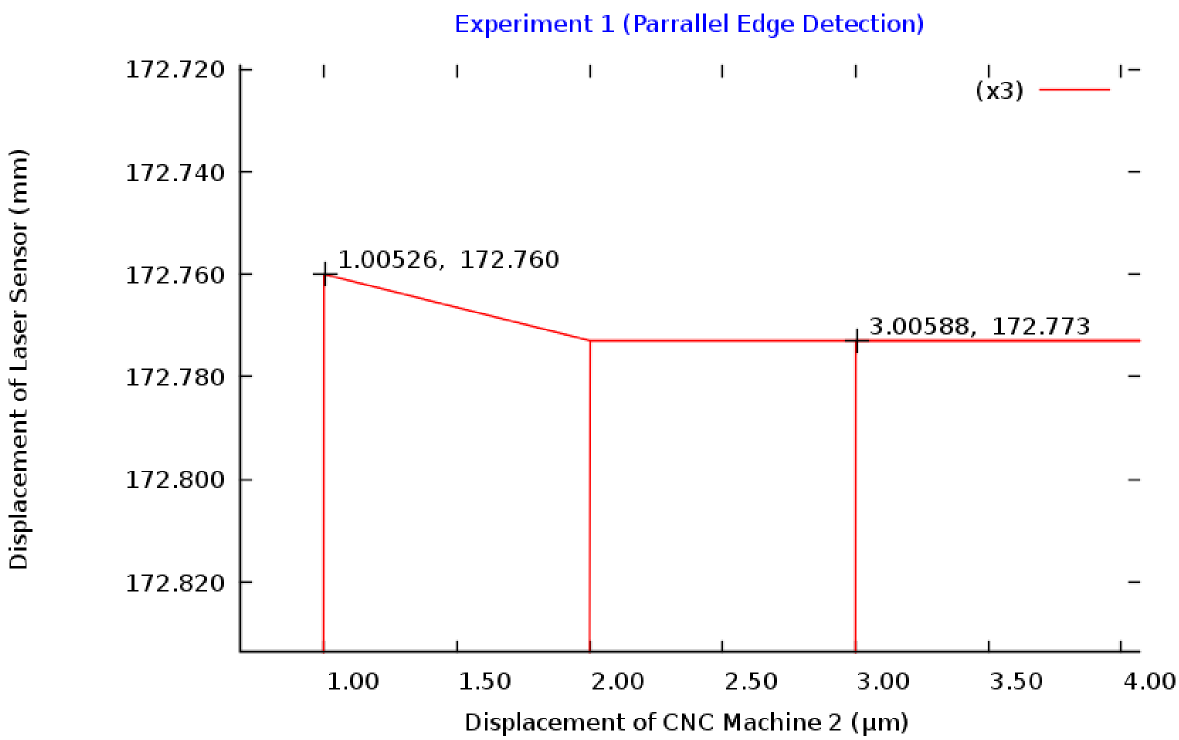


Figure 33 *Resolution of rising parallel edge detection with CNC machine 2 (13 µm)*

8.1.1.2. Resolution of Falling Edge Detection

Furthermore, by zooming into the single step at which the falling edge was detected it can be seen in Figure 34 that the precision of detecting falling edge of the laser sensor is as precise as possible since there is no deviation of measurement values. The resolution is also as high as possible.

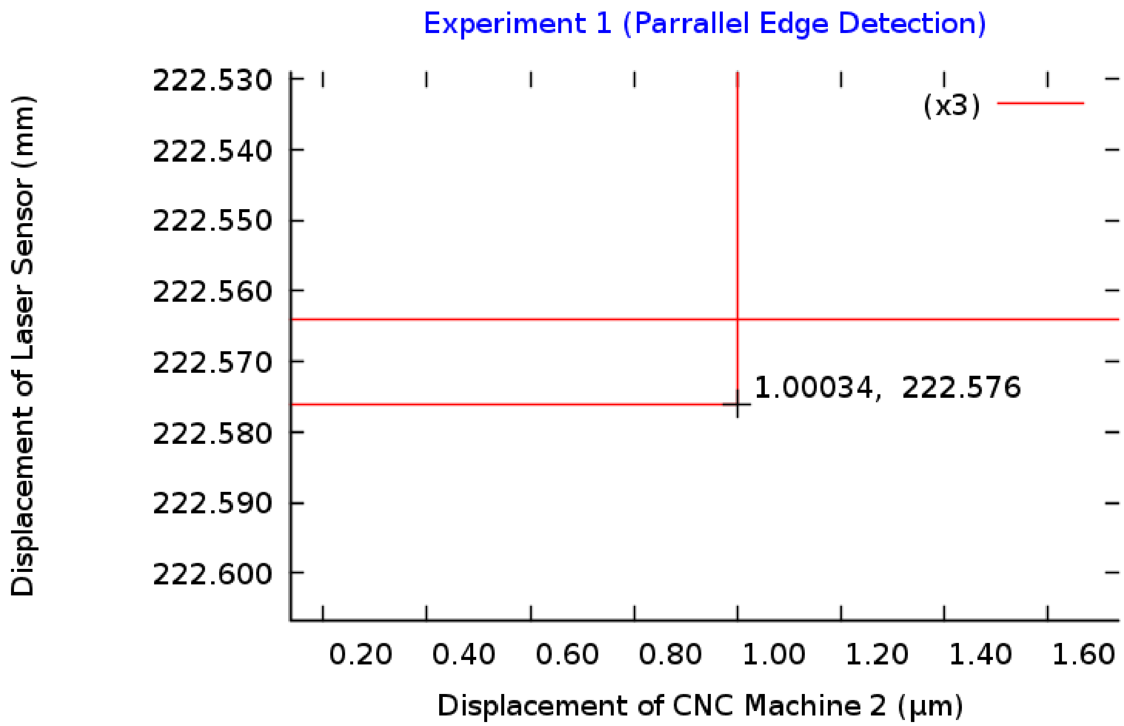


Figure 34 *Resolution of falling edge detection with CNC machine 2*

8.2. Experiment 2 (Perpendicular Edge Detection with Blind spot) Procedure

In this experiment, the laser plane or the laser's angle of deflection was perpendicular to the falling or rising edge that was to be detected as it was shown in Sketch 2 (Pg. 34). This setup results in a blind spot as the laser spot goes off the falling edge thus theoretically transferring measurement values of zero. The laser sensor was supposed to produce actual measurement values only when the rising edge had been detected. Firstly, the laser triangulation sensor was moved to its MMR position relative to the surface of the work piece. Afterwards the laser spot was taken of the edge by moving it in steps of 1 µm each. As the MMR yellow LED was changed to green or red, the position was marked as the reference point of the experiment. After that the laser sensor was moved towards the rising edge and beyond it by 200 µm in an increasing series of steps. The first 10 µm were covered by steps of 1 µm each, following by steps of 10 µm each up to 100 µm and finally by steps of 20 µm each until 200 µm. Then it was moved to the reference point and beyond it in the same increasing series of steps until 200 µm. The measurement value for each point was recorded manually on a piece of paper from the computer which was attached to the FPGA. This measurement cycle was repeated up to 3 times as well. Finally, the data from measurement values were typed in a computer and were graphed with the help of Gnuplot seen in Figure 35.

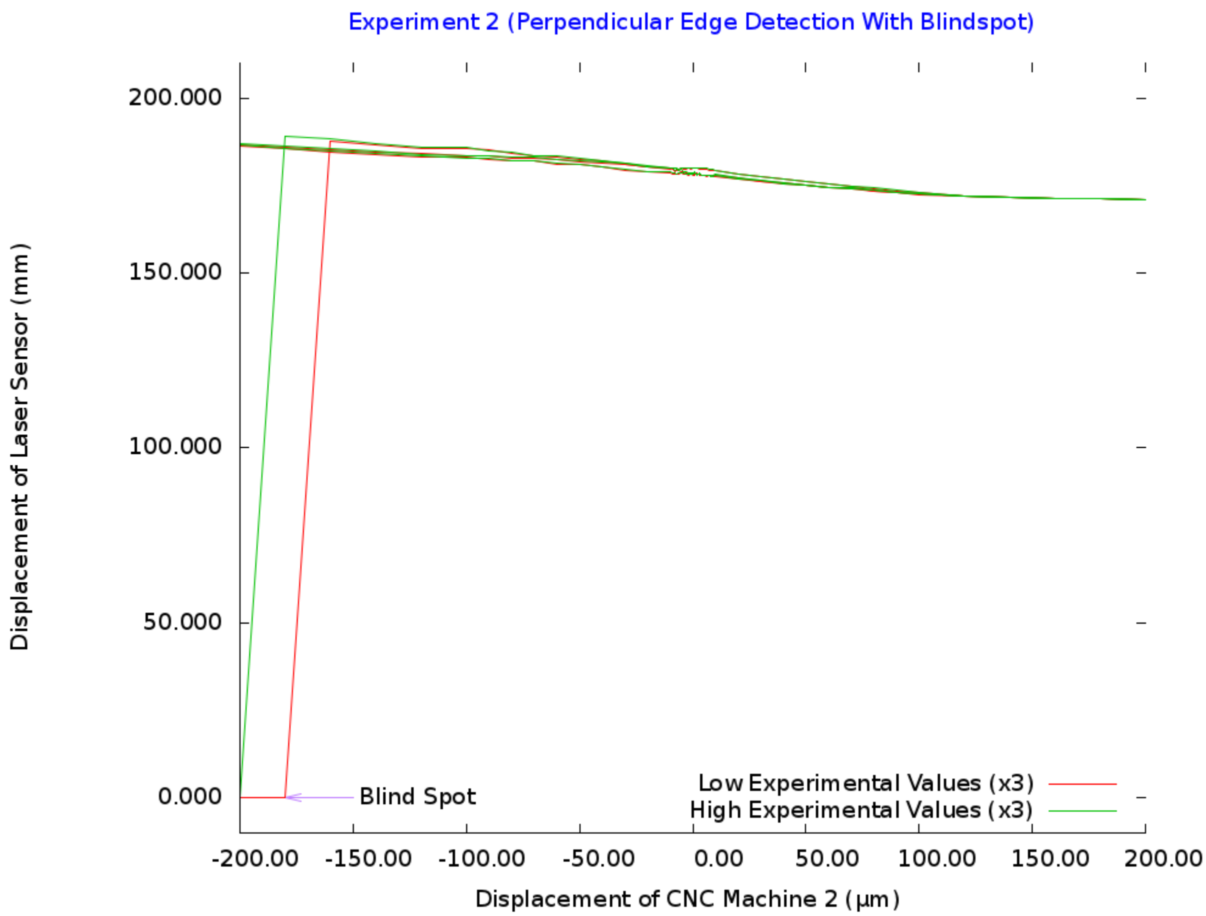


Figure 35 *Result of perpendicular edge detection with blind spot*

8.2.1. Results of Experiment 2

According to Figure 35, the results received when the laser plane or laser's angle of deflection was perpendicular to the edge are very inaccurate as well as imprecise due to the error caused by the blind spot. The measurement values which were received from the laser sensor were very scattered therefore only the highest and the lowest measurement values were recorded and graphed by using Gnuplot as seen in Figure 35. It can be seen that the blind spot was detected at -180 µm and -200 µm of displacement of the CNC machine, however only once in high and low measurement values. Random raw values were still recorded by the sensor when there should have been a blind spot representing a falling edge. It recorded such values due to the scattered light reaching the receiving element (CCD) of the sensor and the fact that it held its previous measurement values to some degree.

8.2.1.1. Resolution and Precision of Rising and Falling Edge Detections

Figure 36 shows the reference point at which falling and rising edge should have been detected but as it can be seen only scattered values with error were recorded by the sensor and no falling edge or blind spot was recorded throughout the measurement cycle. The sensor provided inaccurate and imprecise values with this setup.

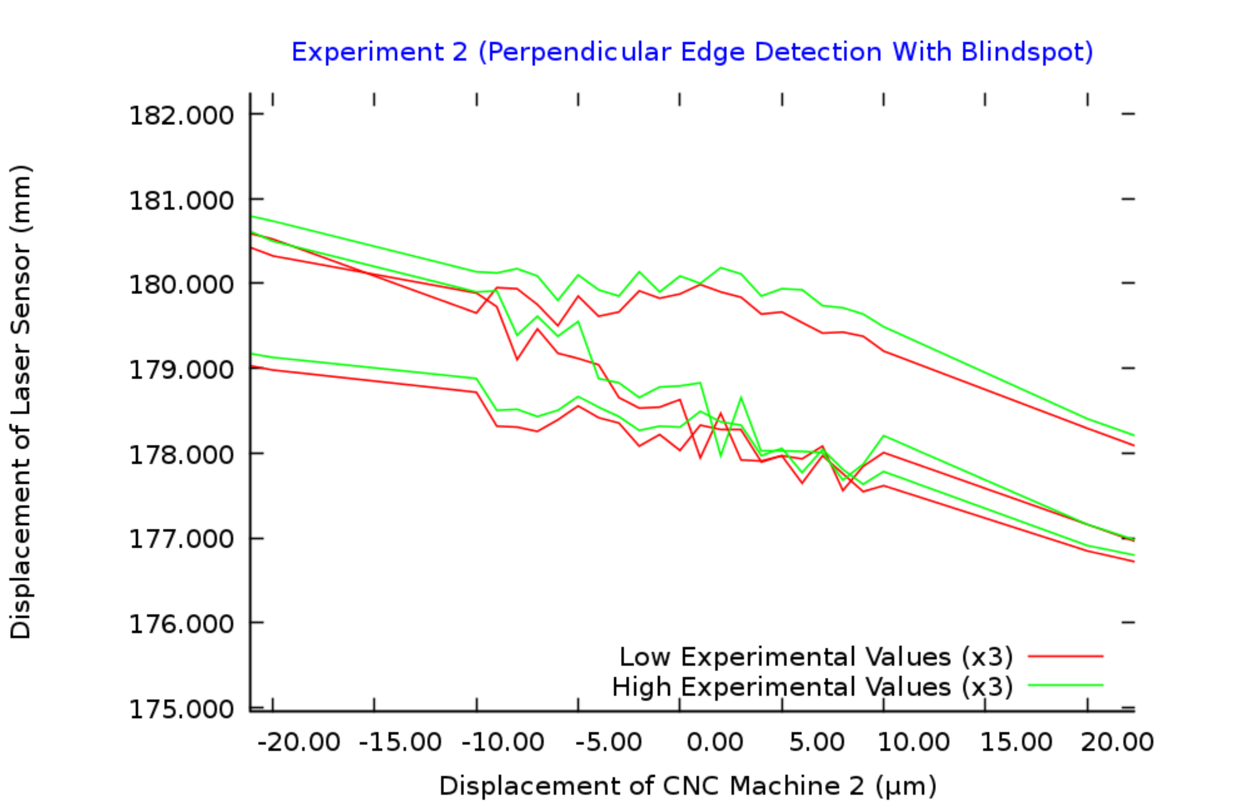


Figure 36 *Resolution and precision of perpendicular edge detection with blind spot with CNC machine 2*

8.3. Experiment 3 (Perpendicular Edge Detection without Blind spot) Procedure

This experiment was conducted following the same principle used in experiment 2 with the CNC machine 2 except the fact that there was no blind spot of the laser during measurement cycle as shown in Sketch 3 on (Pg. 34). The laser plane or the laser's angle of deflection was perpendicular to the rising edge or falling edge. There was no blind spot of the laser since the device was set in such a manner that the laser's angle of deflection was away from the rising edge rather than towards the rising edge followed in Experiment 2. The reference point was marked by the CNC machine following the same procedure as in Experiment 2 as well and the same series of offsets was used. The same measurement cycle was repeated up to 3 times. The measurement value for each point was recorded manually and was graphed with the help of Gnuplot seen in Figure 37.

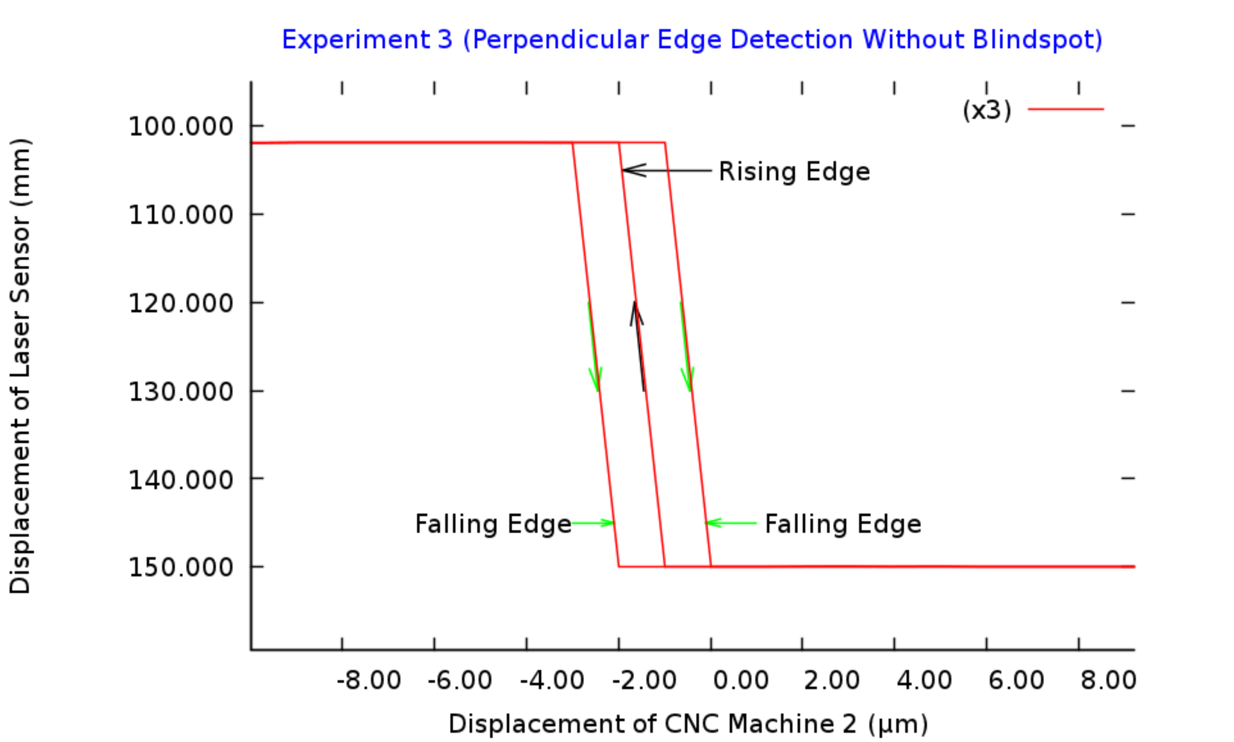


Figure 37 *Results from perpendicular edge detection without blind spot with CNC machine 2*

8.3.1. Results of Experiment 3

In order to understand the results the data were graphed in Figure 37 by using Gnuplot. It can be seen that falling edge is detected at displacement of -2 µm and 0 µm of the CNC machine over the three repeated detections as the displacement of the laser sensor is increased. The rising edge is detected at displacement of -2 µm of the CNC machine over the three repeated detections as the displacement of laser sensor is decreased. The falling edge is detected within 2 µm of displacement of the CNC machine and the rising edge is detected at the same coordinate point or the same displacement of the CNC machine. According to these results the precision of the laser sensor is incredibly precise as in Experiment 1 with the same CNC machine. This is almost the same as the resolution of the CNC machine which is used for this experiment.

8.3.1.1. Resolution of Rising Edge Detection

In addition, by zooming into the single step at which the rising edge was detected it can be seen in Figure 38 that the precision of detecting rising edge of the laser sensor in current setup is as precise as possible since there is no deviation of measurement values. The resolution is also at its peak.

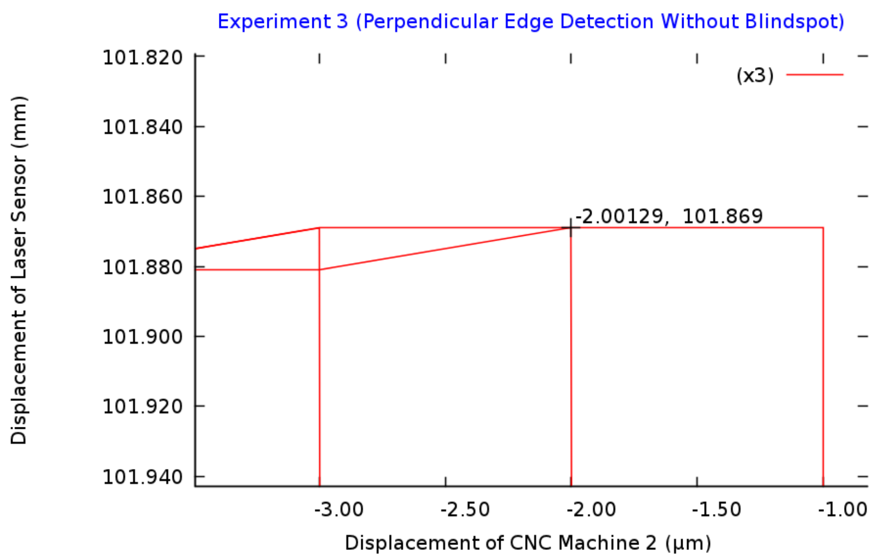


Figure 38 *Resolution of rising edge detection without blind spot with CNC machine 2*

8.3.1.2. Resolution of falling edge detection

By zooming into the two steps at which falling edge was detected it can be clearly seen in Figure 39 that the precision of the laser sensor for detecting falling edge with current setup is as precise as possible since constant measurement values were recorded by the laser sensor.

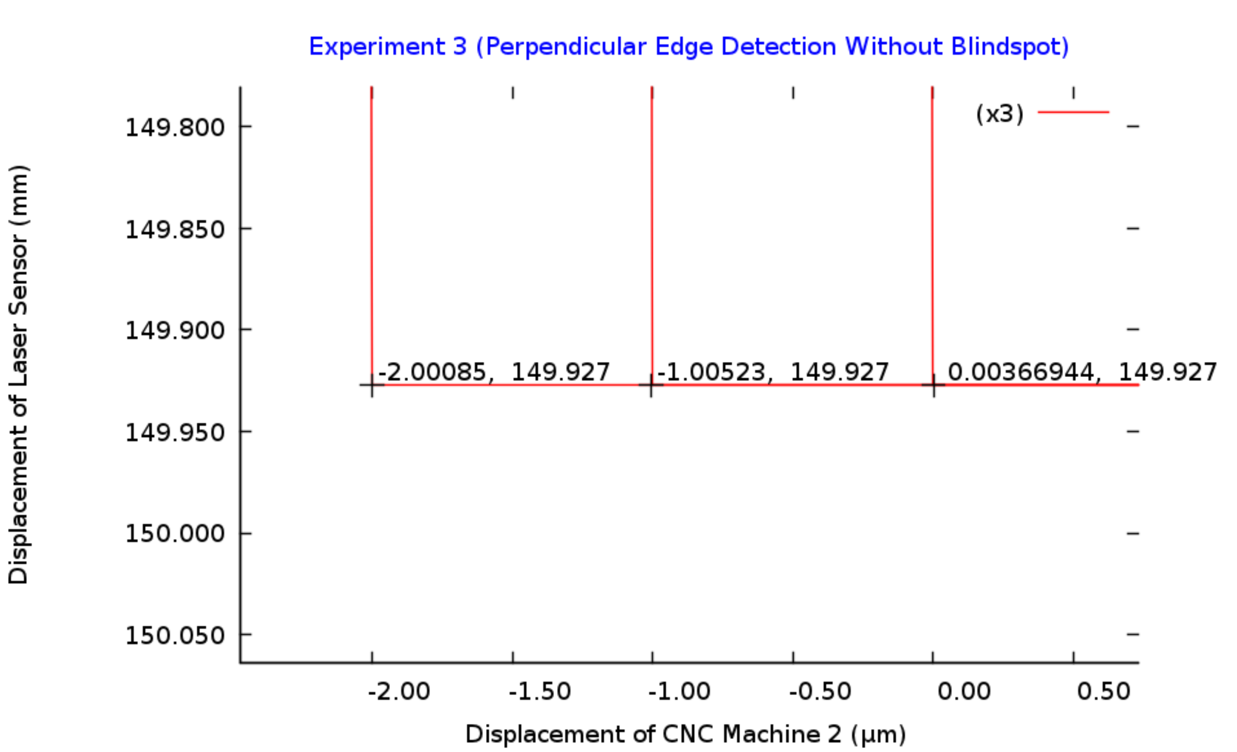
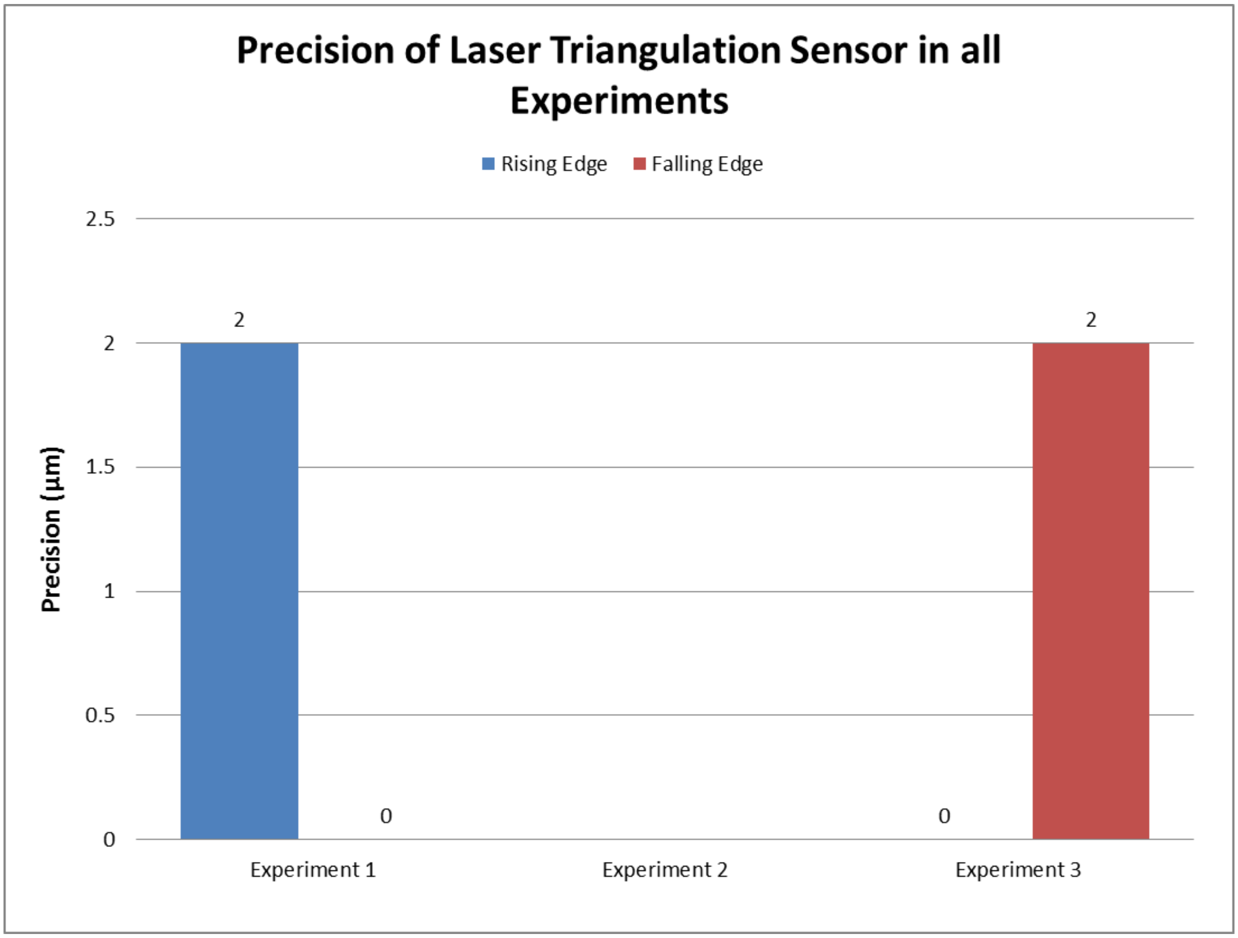


Figure 39 *Resolution of falling edge detection without blind spot with CNC machine 2*

8.4. Edge Detection Conclusion (CNC Machine 2)

According to the results of the laser triangulation sensor received with this CNC machine, it can be concluded that the precision of laser sensor in detecting rising edge in experiment 1 is same as the precision of laser sensor in detecting falling edge in experiment 3 which is 2 µm as seen in Graph 4. In addition, the resolution of detecting rising edge in experiment 1 is 12 µm where as it is 0 µm in experiment 3. Furthermore, the resolution of detecting falling edge in experiment 1 and in Experiment 3 is 0 µm as constant measurement values are received. The resolution of 0 µm is the most precise probably due to the lower repetition of the experiments. Nevertheless it is exceptionally resolute as well as precise. The results received from experiment 2 were simply inaccurate as well as imprecise as the laser sensor transmitted scattered results caused by scattered light received by the high sensitivity element (CCD) of the laser sensor.

In conclusion, the setup in Experiment 1 while laser plane or laser's angle of deflection is parallel to the edge of the work piece to be measured and the setup in Experiment 3 while laser plane or laser's angle of deflection is perpendicular to the edge of the work piece without any blind spots are the best choices for detecting rising edges as well as detecting falling edges since these setups qualify for the highest level of precision along with highest level of resolution of the laser triangulation sensor.



Graph 4 *Precision of the laser triangulation sensor in all experiments conducted with the CNC machine 2*

9. Alternative Opportunities

After thoroughly investigating and analyzing different configuration settings of the laser triangulation sensor (OptoNCDT1700-200), the sensor was unable to provide results lower than 100 µm of linear error for the desired work piece. Different averaging numbers and averaging methods were applied by using different measurement frequencies and feed rates but this linear error was consistent throughout the measurements. After a thorough study it was predicted that if the range of this sensor is decreased, the linear error would also decrease. In order to justify such a prediction, two laser sensors with a measuring range of 40 mm were bought from two different manufacturers which are Micro Epsilon and Keyence. The specifications of these sensors are described in this chapter.

9.1. The OptoNCDT1700-40 Laser Triangulation Sensor

The optical laser triangulation measurement system, ‘OptoNCDT1700-40’ shown in Figure 40, is bought from Micro Epsilon. Its laser triangulation principle and its functional principles with membrane keys are the same as those of the OptoNCDT1700-200 laser triangulation. However, some of its main different specifications are as following (9):

Laser: Pulsed mode semiconductor laser with a wavelength of 670 nm (red)
Power: ≤ 1 mW
Laser Spot Diameter: 230 µm at SMR and EMR, 210 µm at MMR
SMR: 175 mm
MR: 40 mm
MMR: 195 mm
EMR: 215 mm
Resolution: 4 µm
Measuring Frequency: 2.5 kHz
FSO Linearity: 0.08%

The theoretical FSO linear error of this sensor can be calculated by given parameters as following:

$$\pm 0.0008 * 40 \text{ mm} = \pm 0.032 \text{ mm} = \pm 32 \text{ µm}$$

This sensor has a measuring range which is five times smaller than the previous sensor from Micro Epsilon. However its theoretical linear error is about 6 times smaller as well than the previous sensor which is a lot to be taken into consideration. Furthermore, this sensor is much wider than the previous Micro Epsilon sensor as shown in Figure 40, since it had a longer SMR of 175 mm in comparison to the previous sensor which had a SMR of 70 mm. Its laser spot diameter is much smaller than the previous sensor as well which ranges from 230 µm at SMR to 210 µm at MMR and then again to 230 µm at EMR whereas the laser spot diameter of the previous sensor is 1300 µm throughout its measuring range.

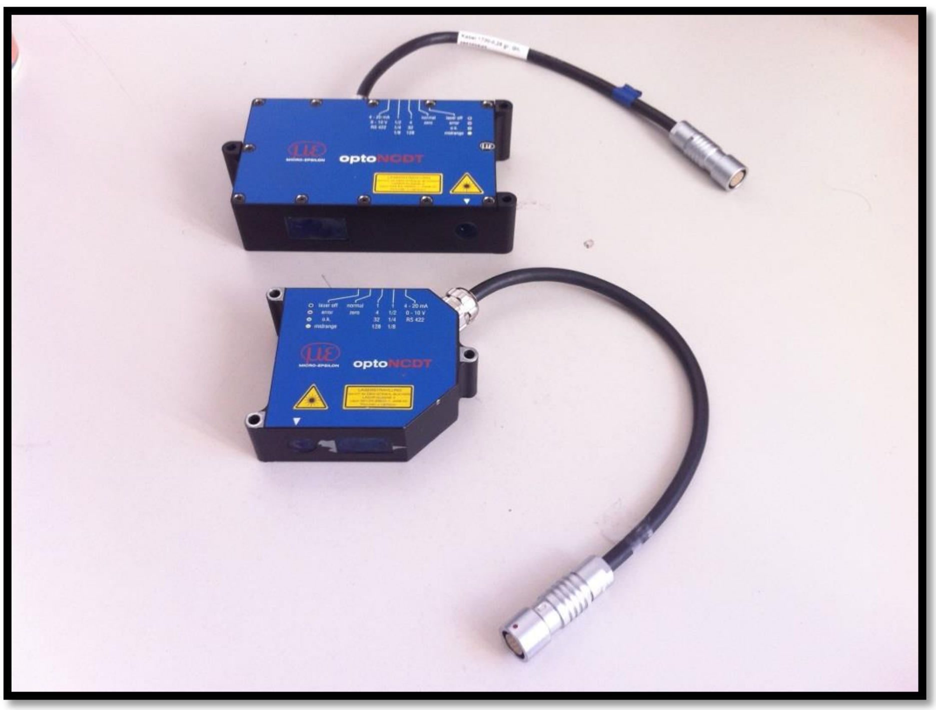


Figure 40 *Micro Epsilon laser triangulation sensors, the optoNCDT1700-200 (Below) and the OptoNCDT1700-40 (Top)*

9.2. The IL-100 Laser Triangulation Sensor

The ‘IL-100’ optical laser triangulation measurement system was bought from Keyence as seen in Figure 41. This sensor also has the same laser triangulation measurement principle as of the other two laser triangulation sensors to measure the displacement over the object. However, its functional principles differ from those other laser triangulation sensors. This laser triangulation sensor consists of a sensor head and a sensor amplifier unit. The sensor head contains the laser diode along with its transmitting lens and the receiving element which transmits an analogue output. The amplifier unit consists of display and a range of buttons for multiple options. The amplifier amplifies the signal received form the sensor head and displays it on its display. This signal in turn is digitalized with communicational unit via RS422 to be processed in a computer. The main specifications of this sensor are as following (6):

Laser: Pulsed mode semiconductor laser with a wavelength of 655 nm (red)
Power Output: 560 µW
Laser Spot Diameter: Approx. 400 * 1350 µm
SMR: 75 mm
MR: 55 mm
MMR: 102.5 mm
EMR: 130 mm
Resolution: 10 µm
Measuring Frequency: 200 Hz
FSO Linearity: 0.15%

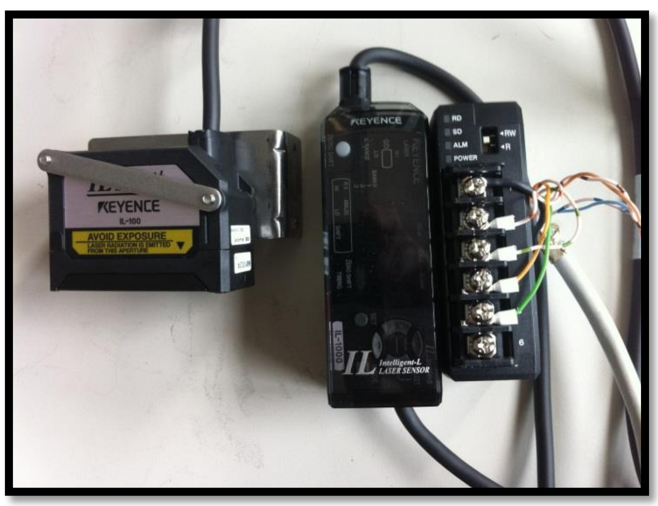


Figure 41 *Keyence IL-100 laser triangulation sensor, its amplifier unit and its communicational unit (Left to right)*

The theoretical FSO linear error of this sensor can be calculated by given parameters as following:

$$\pm 0.0015 * 40 \text{ mm} = \pm 0.060 \text{ mm} = \pm 60 \text{ µm}$$

This laser triangulation sensor has approximately twice as much linear error than the optoNCDT1700-40 but around 3 times lower linear error than optoNCDT1700-200 laser triangulation sensor. Furthermore, the highest measuring frequency of this laser sensor is 200 Hz which is slower than the lowest measuring frequency of the optoNCDT1700-40 laser sensor, which is 312.5 Hz. (6, 9) The sensor head of this laser triangulation measurement unit is much smaller than the Micro Epsilon sensors because its electronics are included in the amplifier rather than the sensor head. This smaller sensor head size provides flexibility for moving and mounting it on wide range of CNC machines. The laser spot diameter of this sensor has an elliptical shape which ranges from 500 * 1550 µm at SMR to 400 * 1350 µm at MMR and again to 500 * 1550 µm at EMR.

10. Measurements by means of the OptoNCDT1700-200 and IL100 Laser Triangulation Sensors

The optoNCDT1700-40 and the IL-100 laser triangulation sensors are thoroughly investigated by taking measurement values of a sample work piece from each sensor using CNC machine 2 which has a theoretical repeatability of 1 µm. These results are explained and cross referenced by the measurement values received from the mechanical inspection probe for the same work piece which has a theoretical repeatability of 1 µm as well.

10.1. Results of all Laser Triangulation Sensors with respect to the Mechanical Inspection Probe

The data from each sensor were received in a series of steps. Firstly, the mechanical probe was referenced with respect to the cornered edge of the work piece. Afterwards, all the optical distance sensors were referenced with respect to their MMR and the cornered edge of the work piece which was clamped in the start of the measurement process. Then, the data were received for each measurement point in steps of 5 mm each for the rough surface of the work piece and 0.5 mm each for the relatively shiny surface of the work piece by each sensor at the same location, individually. Such limited steps were chosen for analysis because each measurement value was typed manually for further investigation, therefore, due to lack of time. Figure 42 illustrates the data of the measurement values plotted in form of line graph using Gnuplot.

According to the graphed data in Figure 42, Figure 43, Figure 44, and Figure 45, it can be seen that the optoNCDT1700-200, represented by a blue line, has the greatest linear error up to 150 µm over the rough surface and up to 300 µm over the shiny surface of the work piece with respect to the measured values of the mechanical probe, Renishaw OMP-40-2, which has a precision of 1 µm.

Moving on, it can be seen from Figure 42 to Figure 45 that the data received from IL100 sensor, represented by a green line is always below the measured values of all the other sensors. Since the work piece was clamped only once in the start of all the measurements and the fact that this optical sensor was referenced similarly to the other optical sensors, it eliminated systematic error to some extent. Furthermore, it can be seen that the graphed data received from IL100 sensor tends to be approximately 100 µm below the rough surface and approximately 500 µm below the shiny surface that was measured by the mechanical probe. This explains that the error is not caused totally due to the clamping or mounting of the work piece. After receiving such bizarre results for IL100 sensor, a decision was made to contact its manufacturer, Keyence. Surprisingly, it had seemed that it wasn't their first encounter with such a dilemma as they had manufactured an external lens which they suggested should solve the problem once it was attached to the receiving lens of the sensor. Nevertheless, there was no possibility to test that external lens due to lack of shipping time.

Last but not least, the optoNCDT1700-40, the laser triangulation sensor with 40 mm range from Micro Epsilon proved to be the most accurate with respect to the mechanical probe as seen in Figure 42, Figure 43, Figure 44 and Figure 45. The measured values differentiated from the mechanical probe's measured values up to 30 µm over the rough surface and up to 60 µm over the shiny surface as shown in these figures. It could be possible that the measurement values taken from this sensor were even more accurate than the measurement values taken from the mechanical inspection probe since this sensor has a much smaller laser spot diameter of 210 µm to 230 µm whereas the mechanical probe has a ball diameter of 3 mm. This means that this laser triangulation sensor is able to measure steeper edges while the mechanical probe is only able to measure the average of top of the edges. In conclusion, this sensor fulfills the accuracy requirement for replacing the mechanical inspection probe which is less than 100 µm.

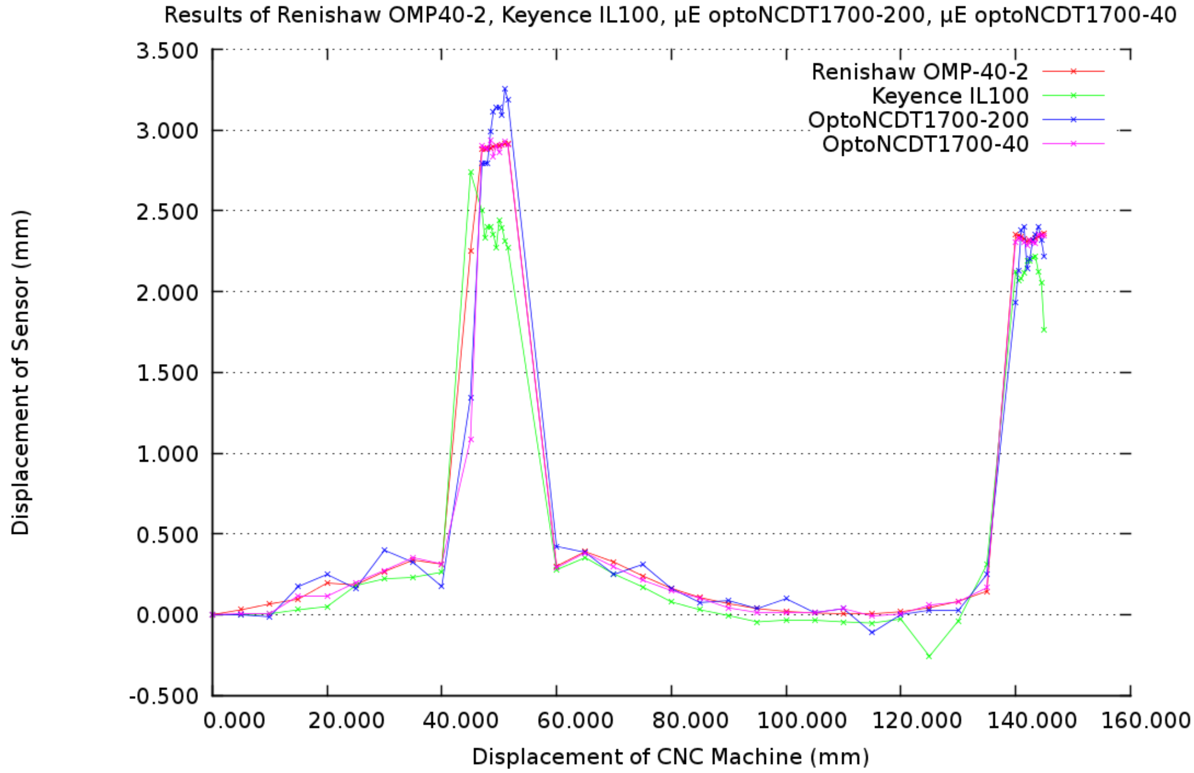


Figure 42 *Results of the mechanical probe, the IL100 laser triangulation sensor, the optoNCDT1700-200 and the optoNCDT1700-40 laser triangulation sensors*

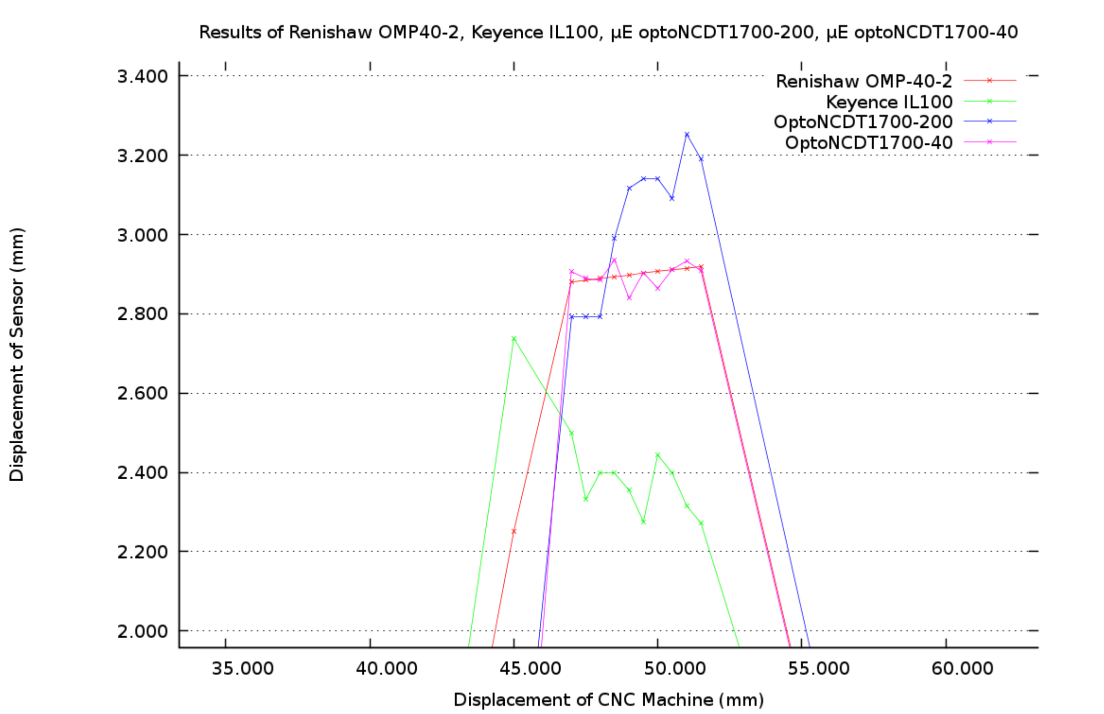


Figure 43 *Zoomed result of the shiny surface measured by mechanical probe and all the optical laser triangulation sensors*

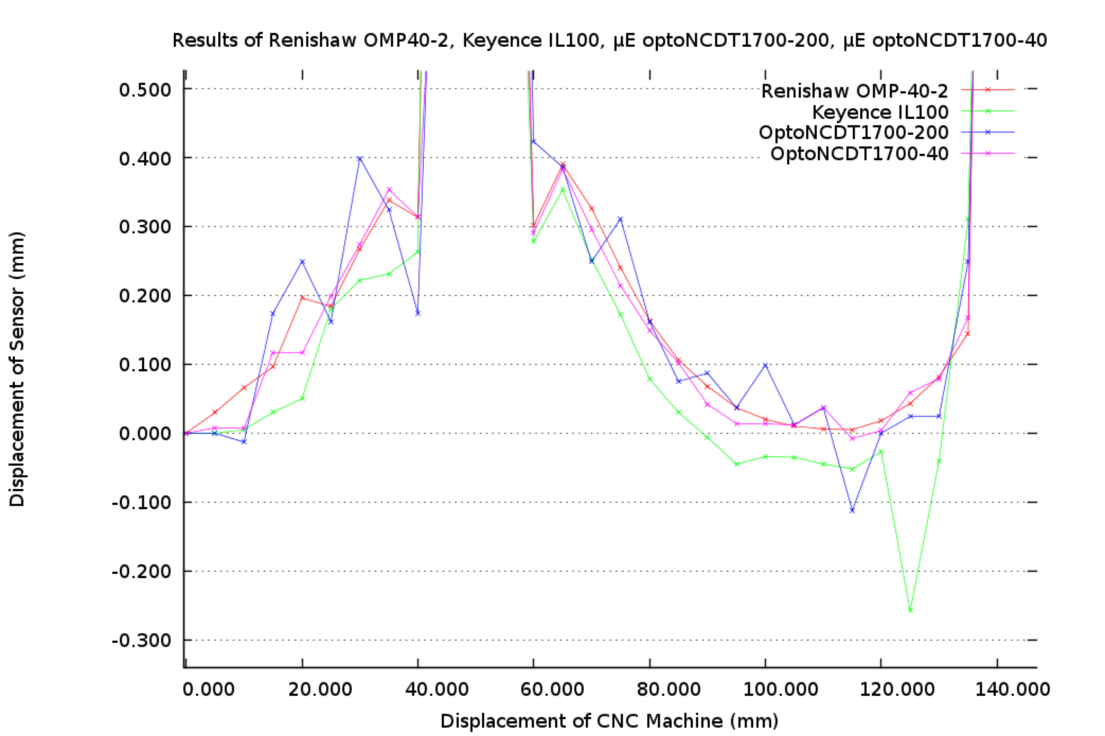


Figure 44 *Zoomed results of the rough surface measured by the mechanical probe and all the optical laser triangulation sensors*

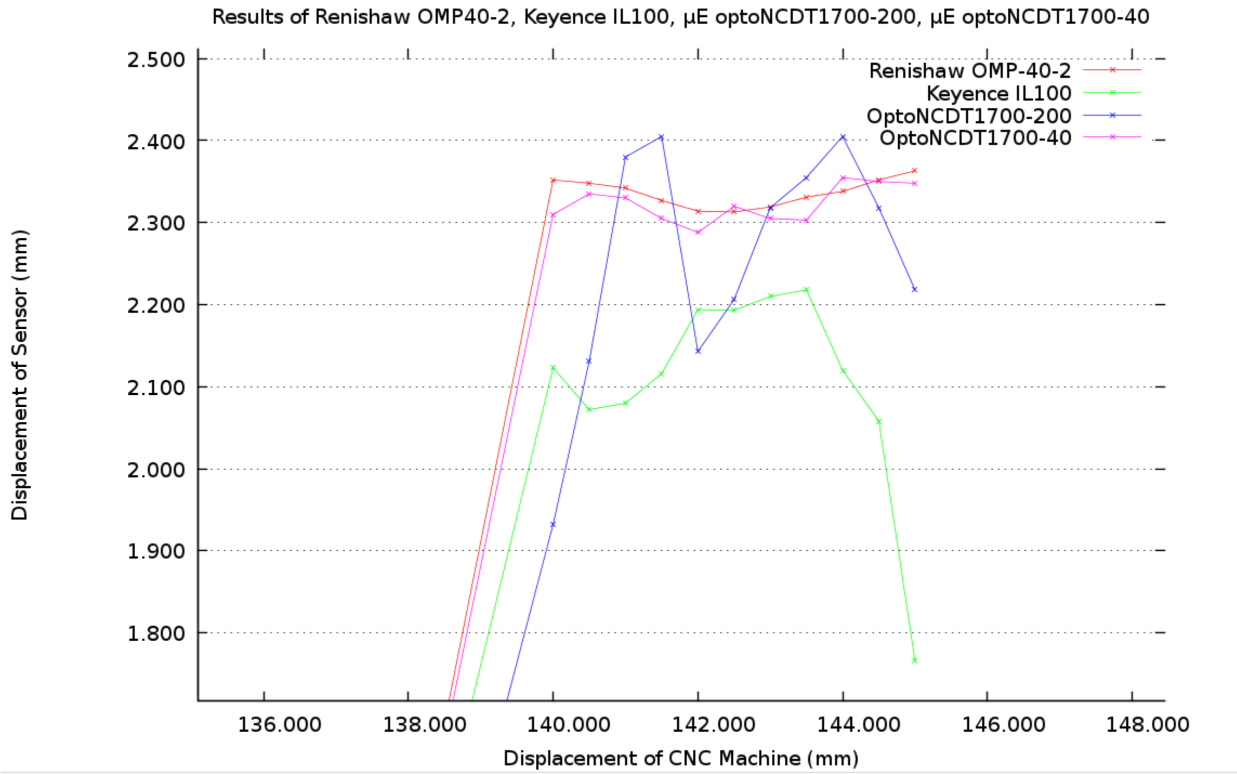


Figure 45 *Zoomed result of the shiny surface measured by mechanical probe and the optical laser triangulation sensors*

10.2. Further Investigation of the OptoNCDT1700-40 Laser Triangulation Sensor

As the laser triangulation sensor, ‘optoNCDT1700-40’ provided the best results out of all the other optical laser triangulation sensors and fulfilled the accuracy requirement for replacing the mechanical inspection probe. It was further analyzed and investigated to provide concrete evidence of its capabilities. Therefore, it was tested to take repeated measurement values when its laser plane was parallel to the surface roughness and when its laser plane was perpendicular to the surface roughness. Additionally, these results were cross referenced with the measurement values taken from the mechanical inspection probe.

10.2.1. Procedure of further Analysis and Investigation

Initially, the work piece was clamped on the working area of the CNC machine 2 and it was not disturbed throughout the measurement process to avoid systematic error. Then, the mechanical inspection probe and the laser triangulation sensor were referenced with respect to the cornered edge of the work piece one after another. The mechanical probe was referenced by contacting the cornered edge and the laser triangulation sensor was referenced with respect to its MMR. After referencing, measurement values were taken in a series of steps from both sensors. Steps of 5 mm each were selected for the rough surface and steps of 0.5 mm were selected for the relatively shiny surface of the work piece. Finally, the measurement process was started by taking and recording measurements with the mechanical probe. Then, the measurements were taken at relatively same location of the work piece by the laser triangulation sensor and this measurement process was repeated up to 5 times. The whole measurement process was conducted twice, once when the laser sensor’s plane was parallel to the surface roughness of the work piece and the other when the laser sensor’s plane was perpendicular to the surface roughness of the work piece.

10.2.2. Results of further Analysis and Investigation

Figure 46 shows the plotted result received from the parallel measurement process and the perpendicular measurement process of the optoNCDT1700-40 laser triangulation sensor. First of all, it can be seen from this figure that the result received from the parallel measurement process tends to move lower from left to right for the measurements over the surface. This is caused by systematic error due to clamping of the work piece. The work piece was clamped tighter on the left side in contrast with right side as the measurement values were not as low as they tend to be on the right side of the work piece as shown in Figure 46 and Figure 47.

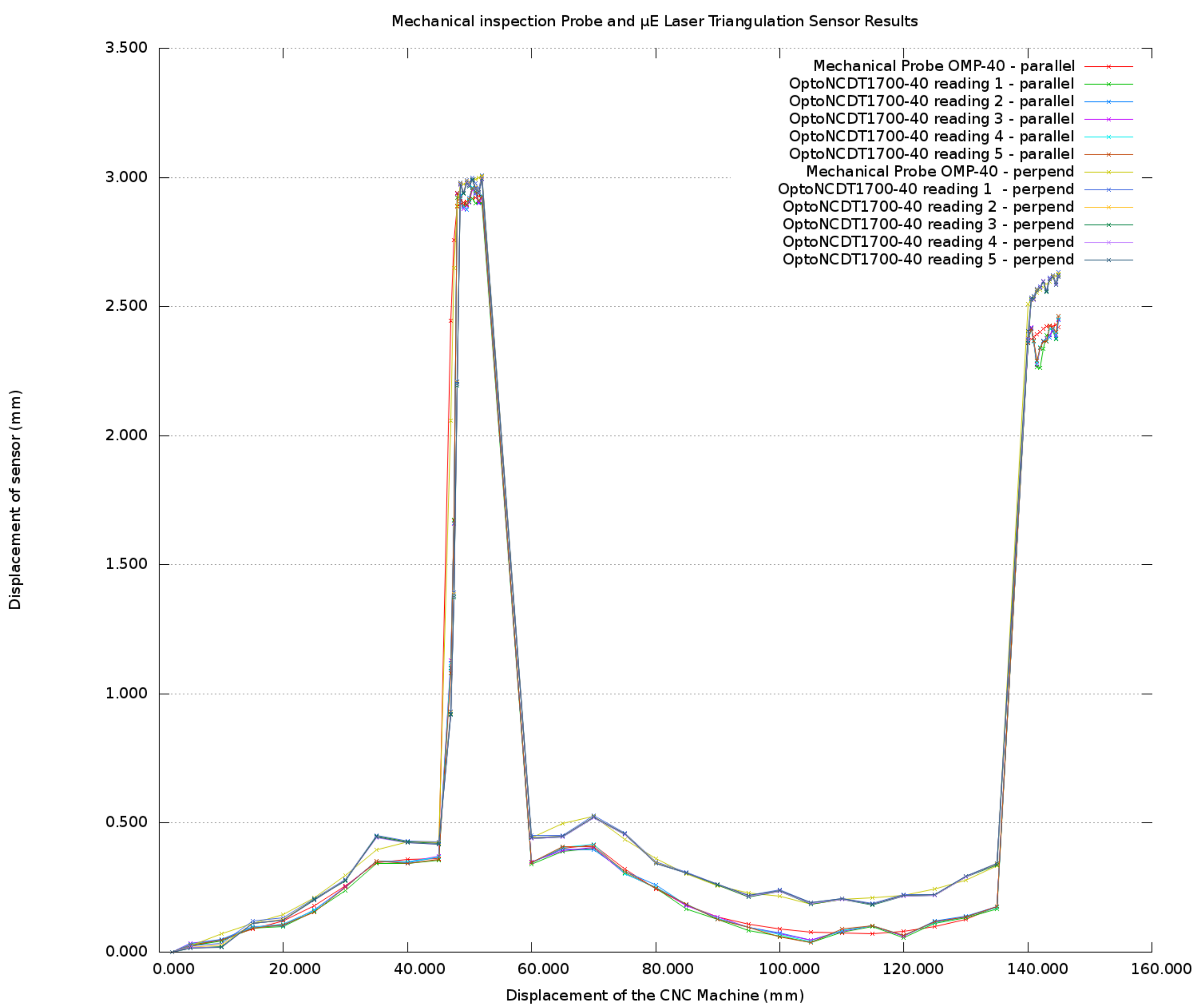


Figure 46 *Result of parallel and perpendicular measurement processes by the optoNCDT1700-40 laser triangulation sensor*

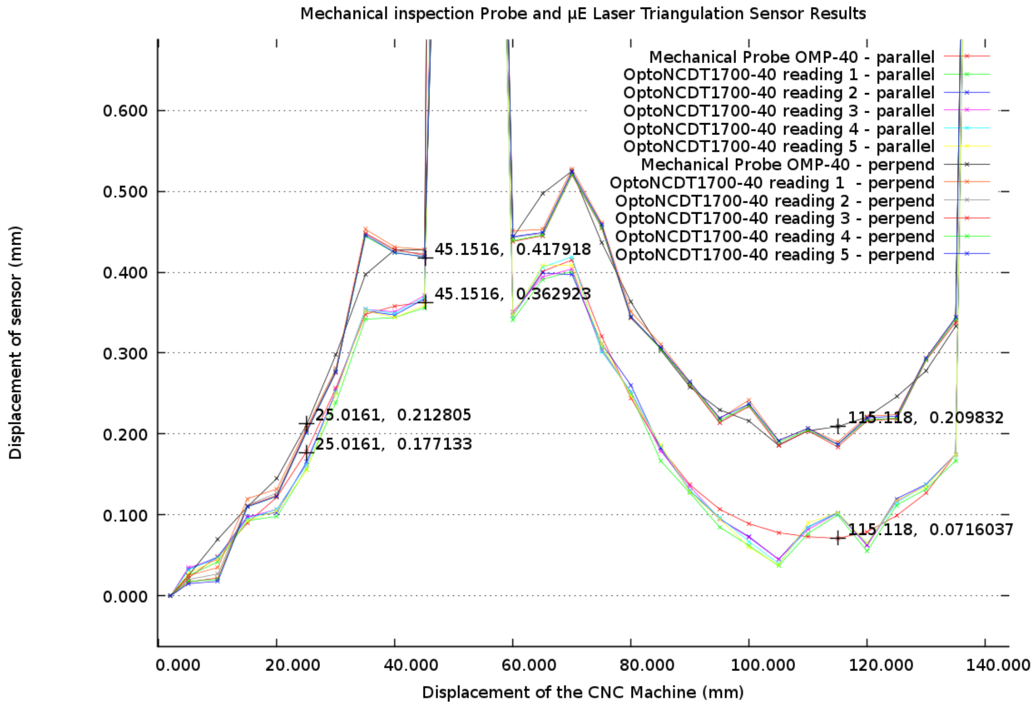


Figure 47 *Zoomed rough surfaces of parallel and perpendicular measurement processes by the optoNCDT1700-40 laser triangulation sensor*

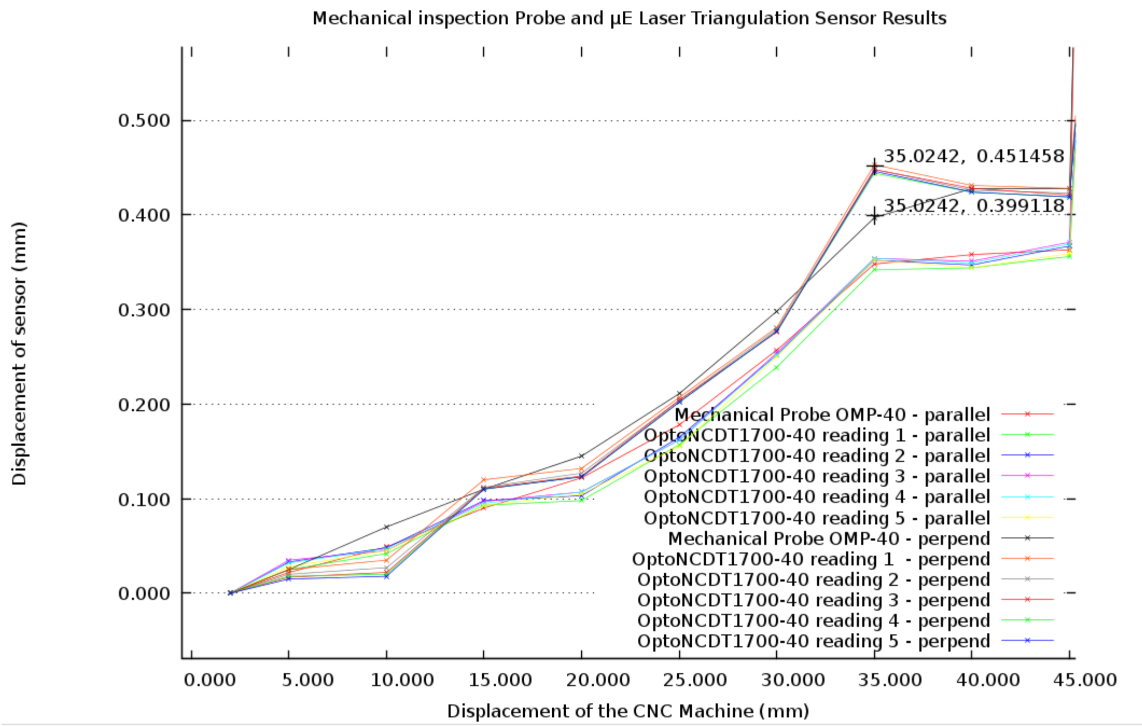


Figure 48 *Zoomed rough surface of parallel and perpendicular measurement processes by the optoNCDT1700-40 laser triangulation sensor*

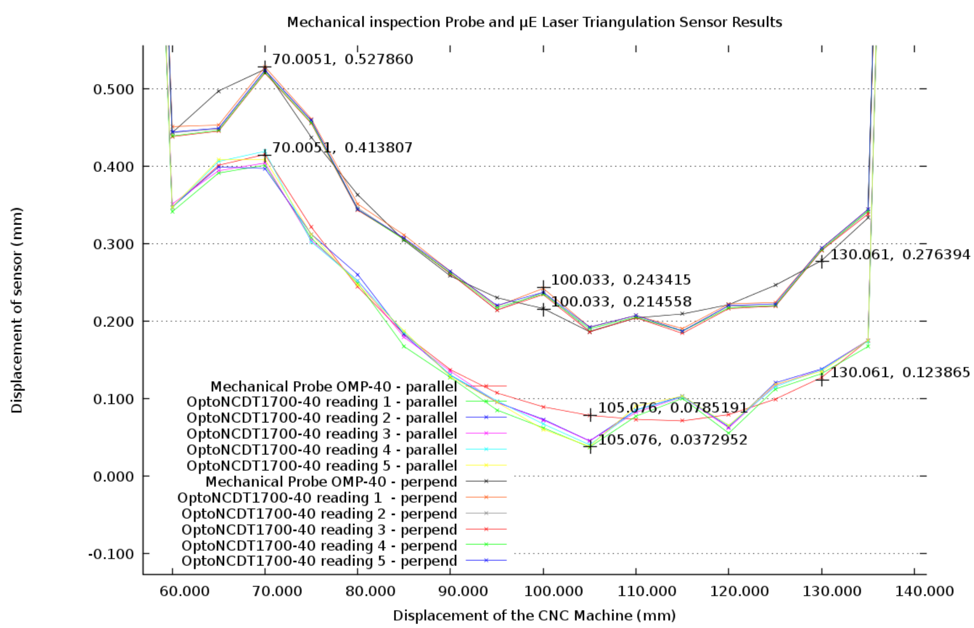


Figure 49 *Zoomed rough surface of parallel and perpendicular measurement processes by the optoNCDT1700-40 laser triangulation sensor*

Furthermore, it can be seen from Figure 48 and Figure 49 that the maximum displacement of the laser sensor with respect to the mechanical probe is approximately 40 µm for the parallel measurement process and approximately 60 µm for the perpendicular measurement process over the rough surface of the work piece. It can be concluded from this result that this indirect reflection sensor is quite suitable for the rough surface. It gives an acceptable result for even the shiny surface, however with full linear error. In theory, direct reflection sensor is the most suitable for shiny surfaces.

Moving on, Figure 50 and Figure 51 show that the laser sensor has an overall better displacement measuring result in perpendicular measurement process rather than for parallel measurement process over the shiny surface of the work piece. After receiving such result, the shiny surface was analyzed more carefully and it was observed that the surface had thin machined lines which were approximately perpendicular to the relatively larger lines of the rough surface of the work piece. The laser sensor provided better result when its laser plane was parallel to the surface roughness of the part because the deflected element of the laser beam was not disrupted by perpendicular lines. It can also be seen from Figure 50 and Figure 51 that the maximum difference in displacement of the laser sensor with respect to the mechanical probe is approximately 130 µm for the parallel measurement process and approximately 65 µm for the perpendicular measurement process. This is because the actual surface is perpendicular instead of parallel and vice versa.

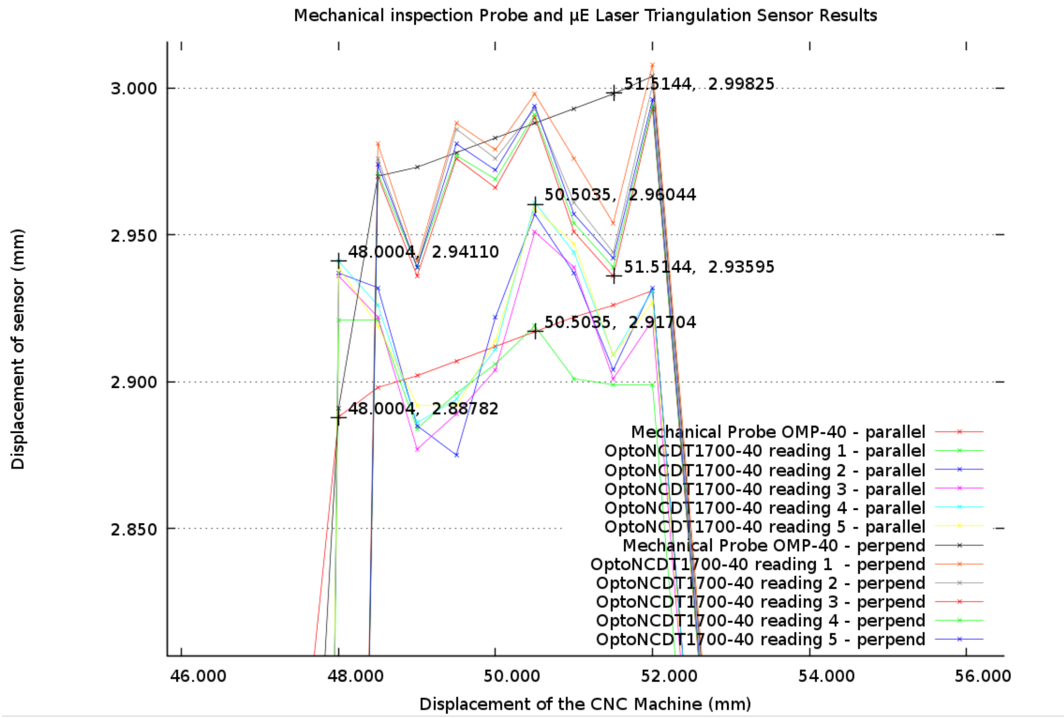


Figure 50 *Zoomed shiny surface of parallel and perpendicular measurement processes by the optoNCDT1700-40 laser triangulation sensor*

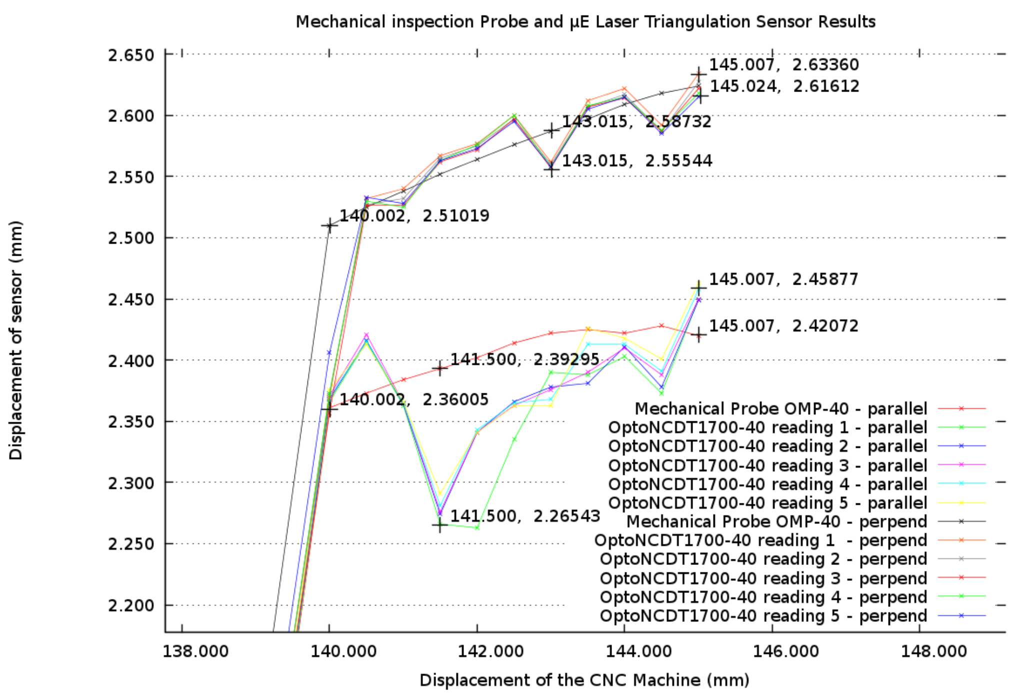


Figure 51 *Zoomed shiny surface of parallel and perpendicular measurement processes by the optoNCDT1700-40 laser triangulation sensor*

11. Summary

This thesis has thoroughly investigated the optical distance sensors in the tool industry in order to replace a mechanically operated probe measurement system to decrease machine down time along with cost and hence to increase productivity.

After theoretical studies of the optical principles of the confocal chromatic sensor and the laser triangulation sensor both, optical sensors were bought, investigated, tested and programmed with the selected CNC machines. As a result both sensors, that is, the optoNCDT1700-2401 confocal chromatic and the optoNCDT1700-200 laser triangulation sensor with specific features are unable to satisfy the desired requirements due to lack of measurement range for detecting edges or due to excessive measurement range with too much linear error, respectively. However, the laser triangulation sensor that had the capability of measuring the desired edges of the sample work piece was investigated for edge analysis with different angles of laser plane with two different CNC machines to state the best way of measuring edges. As a result, the laser triangulation sensor qualifies for the highest level of precision along with highest level of resolution of the laser sensor when its plane or its angle of deflection is parallel to the rising or falling edge of the sample part. In addition, it is observed that the setup in which the laser's plane is perpendicular to the edge of the part without any blind spots can also be considered to measure edges provided that it is integrated with a CNC machine which has a high level of resolution.

Meanwhile, after thorough investigation, it was predicted that the linear error in accuracy of the optical distance sensors decreases with decreasing measurement range. In order to justify such a prediction, two laser triangulation sensors with shorter range were bought from two different manufacturers, Micro Epsilon, and Keyence. These sensors were analyzed and investigated with respect to the mechanical inspection probe.

As a result of this thesis, the optoNCDT1700-40 laser triangulation sensor, from Micro Epsilon fulfills all the requirements by proving to be the most efficient, reliable, affordable, accurate and precise laser sensor that could replace the relatively time consuming mechanical inspection probe to measure the distance, displacement and edges of work pieces up to 40 millimeters. This sensor fulfills the requirement of having higher measuring frequency which ranges from 312.5 Hz to 2500 Hz. With this measuring frequency, there is approximately no limit for the feed rate of the CNC machine for taking the measurements as it can take 312.5 to 2500 measurement values per second. Therefore, it can take measurement readings as fast as the CNC machines are able to move themselves because these machines have limited speed with respect to the measuring frequency of this laser sensor. It also fulfills the requirement of measuring displacement with an accuracy of less than 100 µm. It is measured to be approximately 65 µm with respect to the mechanical inspection probe for the sample part. Furthermore, as this laser triangulation sensor has the same manufacturer, same design, same features and specifications except for the MR as the OptoNCDT1700-200, it can be concluded that it is very accurate as well as precise with an accuracy of 1 µm to 2 µm at detecting rising edges or falling edges of the sample work piece. This accuracy of detecting edges is extremely higher than the accuracy of the mechanical inspection probe for detecting edges. The mechanical inspection probe detects filtered edges of up to 1.5 mm with a repeatability of 1 µm with a high resolution CNC machine 2. However, this laser sensor can detect true edges with a repeatability of 1 µm to 2 µm with a high resolution CNC machine 2. Last but not least, this sensor was further investigated to achieve paramount results. Consequently, it is observed that it measures most accurately when its laser plane is parallel to the surface roughness of the work piece. Finally, usage diagram, activity diagram, and state diagrams are created for recommendations of the measurement cycle of this laser triangulation sensor.

12. List of Figures

13. List of Sketches

14. List of Graphs

15. List of Tables

16. Bibliography

1. *Sensors and Actuators*. (2009). Retrieved 4-7 2013, from The learning place for sensors and actuators: http://sensors-actuators-info.blogspot.de/2009/08/laser-triangulation-sensor.html

2. *Touch probes for machine tools*. (2013). Retrieved 5-7 2013, from HEIDENHAIN GmbH: http://www.heidenhain.com/en_US/products-and-applications/setup-and-measurement/touch-probes/

3. Hindawi Publishing Corporation. (2012). *Hindawi Publishing Corporation*. Retrieved 6 2013, from ISRN Renewable Energy: http://www.hindawi.com/isrn/re/2012/746865/fig6/

4. Hoffmann GmbH. (2013). *Digital Caliper*. Retrieved 8 2013, from Hoffmann Group: http://eshop.hoffmann-group.com/icon/catalogs/EN/K44/pdf/412601.pdf

5. Keyence. (2013). *Laser Displacement Sensors*. Retrieved 5-7, from Keyence Corporation: http://www.keyence.ca/products/measure/laser/laser.php

6. Keyence Corporation. (2012). *IL Series User's Manual.* Osaka, Japan: Keyence.

7. Micro Epsilon. (2013). *Glossary: Confocal Chromatic.* Retrieved 06 1, 2013, from Micro-Epsilon Messtechnik GmbH & Co. KG, Germany: http://www.micro-epsilon.com/glossar/Konfokal-chromatisch.html

8. Micro Epsilon. (2013). *Glossary: Laser Triangulation.* Retrieved 4-7 2013, from Micro-Epsilon Messtechnik GmbH & Co. KG, Germany: http://www.micro-epsilon.com/glossar/Laser-Triangulation.html

9. MICRO-EPSILON. (2008). *Instruction Manual OptoNCDT 1700.* Ortenburg: Micro Epsilon.

10. MICRO-EPSILON. (n.d.). *Instruction Manual OptoNCDT 2401.* Ortenburg: Micro Epsilon.

11. Micro-Epsilon Messtechnik GmbH & Co. KG. (2013). *Glossary*. Retrieved 8 2013, from Micro Epsilon: http://www.micro-epsilon.com/glossar/Linearitaet.html

12. Renishaw. (2001-2013). *OMP40-2 Compact Touch Probe.* Retrieved 5-7 2013, from Renishaw plc Web site: http://www.renishaw.com/en/omp40-2-compact-touch-probe--7992

13. Renishaw plc. (2008, 8). *OMP40-2 Compact Touch Probe: Data Sheet.* Retrieved 8 2013, from Renishaw Apply Innovation: http://www.renishaw.com/en/omp40-2-compact-touch-probe--7992

14. SensorsONE Ltd. (2013). *Glossary Index*. Retrieved 8 2013, from SensorsONE Pressure Measurement Instruments: http://www.sensorsone.co.uk/pressure-measurement-glossary.html#f-words

15. Wiki media. (2013, 6). *Charge coupled device*. Retrieved 6 2013, from Wikimedia Foundations Inc.: http://en.wikipedia.org/wiki/CCD_array

16. Wikimedia. (2013, 7). *Chromatic Aberration.* Retrieved 4-7 2013, from Wikimedia Foundation Inc.: http://en.wikipedia.org/wiki/Chromatic_Aberration

17. Wikimedia. (2013, 6). *Laser*. Retrieved 4-7 2013, from Wikimedia Foundations Inc.: http://en.wikipedia.org/wiki/Laser

18. Wikimedia Commans. (2013, 4). *Dispersion Curve*. Retrieved 6 2013, from http://commons.wikimedia.org/wiki/File:Dispersion-curve.png

19. Wikimedia Foundation, Inc. (2013, 3). *Chromatic abberation lens Diagram.* Retrieved 7 2013, from Wikipedia: http://en.wikipedia.org/wiki/File:Chromatic_abberation_lens_diagram.svg