DAS **Departamento de Automação e Sistemas**
CTC **Centro Tecnológico**
UFSC **Universidade Federal de Santa Catarina**

Integration of a laser scanner into a machine tool for an in-process 3D measurement

Monografia submetida à Universidade Federal de Santa Catarina
como requisito para a aprovação da disciplina:
DAS 5511: Projeto de Fim de Curso

João Paulo de Moraes Paludo

Aachen, Julho de 2012

Integration of a laser scanner into a machine tool for an in-process 3D measurement

João Paulo de Moraes Paludo

Orientadores:

Dipl.-Wirt.-Ing. Martin Peterek |WZL-RWTH

____

Assinatura do Orientador

Prof. Dr.-Ing. Marcelo Ricardo Stemmer

____

Assinatura do Orientador

Este relatório foi julgado no contexto da disciplina
DAS 5501: Estágio e Controle e Automação Industrial
e aprovado na sua forma final pelo
Curso de Engenharia de Controle e Automação

Acknowledgements

In the first instance I must thank my parents Clara and Isauro Paludo and my brother Luis Guilherme Paludo, for all the attention, care, love and dedication during the whole time I was involved in completing this internship project. They were the force that I needed to move on, when an obstacle was placed in the path of success of this project.

I'm also thankful for all the company, love, help and patience that Alana Franca dedicated to me during this last six months.

To my mentors Martin Peterek and Marcelo Stemmer, thank you for your help, patience, understanding, counsel, and for all the time that was dedicated to me during these past months.

I'm also need to say thanks to my project colleague , Arno Berghoff for the all the company and time that we spent together inside and outside the institute.

To my new friends in Aachen, Assuero, Benedikt, Bruno, João and Eduardo. Not only them but my old friends Igor, Leandro and Tarik.

Abstract

In the actual state of the manufacturing technology, the new products are gaining more details and therefore becoming increasingly complex. Not to mention the range of fragile products. The turbine blades are an example for big, fragile and highly strained machine parts. At the same time the quality process needs to be thorough and with small tolerances.

Nowadays, most of the components processed on a machine tool, are inspected after the machine process. In a another environment a quality inspection is made, which in turn brings additional costs with transportation, machine setup, not counting the time that were spent during all this cycle.

The introduction of a new tool, that could inspect the parts, into the machine-tool could give more agility and less costs during the whole fabrication and inspection of the manufactured parts. A well-spread inspection tool, who attend the all of the short requirements, is the laser scanning technology. Using this solution, it will be automatically employed a non-contact measuring procedure to the quality inspection process.

This document will describe the research, analysis and the development of a possible implementation a laser scanning measurement-processes into the machine-tool, looking forward to inspect the quality of components, just after the machining process.

Resumo estendido

Foram três as tecnologias que ao se desenvolverem, enunciaram a visionários o surgimento de uma nova era na tecnologia que muitos estudiosos chamam de a nova era da indústria. São elas: as máquinas ferramenta, a automação e a informática.

A revolução industrial pode ser dita que se iniciou com o escocês James Watt (projetando a máquina a vapor), deste modo ele também criou a necessidade pela indústria de máquinas ferramenta. Pois ficou bastante óbvio que sem uma máquina ferramenta que usinasse cilindros com razoável precisão ele não poderia construir motores, porque não havia meios de usinar cilindros nos seus primeiros empenhos.

Ainda neste mesmo contexto histórico, houve outro desenvolvimento necessário para a introdução das ferramentas controladas por números, o desenvolvimento de controles automáticos. É nesta brecha que a automação e a informática se inserem na tecnologia de comandos numéricos associadas as máquinas ferramenta.

A partir dai, o mundo destas máquinas vem mudando a cada dia mais, novas ferramentas e funções tem sido integradas a uma única máquina. Máquinas que atualmente são chamadas, e verdadeiramente são centros de usinagem.

É no intuito de novamente inovar e agregar uma nova função aos centros de usinagem que este projeto busca se posicionar. Neste, é colocado como objetivo a introdução de uma nova ferramenta para inspeção de qualidade em peças recém usinadas. Para isto, o Instituto de pesquisa e desenvolvimento WZL, através de parcerias firmadas com fabricantes alemães de máquinas CNC e scanner laser, propõem o desenvolvimento deste novo projeto para a integração de um sistema de inspeção pós usinagem. Desta maneira, o projeto visa minimizar os custos envolvidos no transporte da peça, tendo em vista uma vistoria dos seus padrões de qualidade.

Mais do que isto, a integração do scanner laser busca flexibilizar o processo de controle de qualidade. Devido a característica do processo de escaneamento

laser ser não táctil tanto, peças frágeis ou robustas, podem ser processadas sem causar danos como riscos ou quebras.

Este trabalho contém as atividades desenvolvidas pelo acadêmico João Paulo de Moraes Paludo, referente à integração de um laser scanner Nokra Taglio à máquina CNC Hermle modelo C 800 U. Este projeto visa descobrir, limitações, dificuldades, soluções e resultados que podem ser impostos ao se integrar dois dispositivos não interconectáveis.

No princípio do documento, será apresentada uma revisão objetiva dos conceitos e fundamentos que levaram ao advento dos equipamentos. Também é descrito o contexto onde se insere o projeto, que visa empregar a metrologia dentro das máquinas ferramentas através da tecnologia laser.

O capítulo três descreve em particular a máquina CNC e o scanner laser utilizados durante o projeto. Tendo em vista que cada um possui suas características e um princípio específico.

No decorrer do capítulo quatro, demostra-se os esforços necessários para as diferentes integrações que tiveram de ser efetuadas para que os modelos 3D pudessem ser gerados. Primeiramente são descritos os artifícios usados para uma integração de hardware entre os dois aparelhos. E logo em seguida, uma apresentação das transformações e modelo cinemático da máquina CNC são expostos. Assim, finalizando o capítulo quatro, a integração de software necessária para aquisição de dados e tratamento dos mesmos para a construção de um modelo 3D do objeto escaneado.

No capítulo cinco, discute-se brevemente os resultados obtidos analisando os problemas e possíveis soluções.

Finaliza-se o documento com uma conclusão a respeito do que foi alcançado, e sugestões para o desenvolvimento de futuros passos a serem seguidos afim de alcançar resultados ainda melhores.

Contents

Simbology

Acronyms

RWTH - Rheinisch-Westfaelische Technische Hochschule.

WZL - Werkzeugmaschinenlabor. (Laboratory for machine Tools and Production Engineering)

CAD - Computer-Aided Design

CAM – Computer-Aided Manufacturing

Matlab - Matrix Laboratory

LabVIEW – Laboratory Virtual Instrumentation Engineering Workbench.

CNC – Computerized Numerical Control.

Laser – Light Amplification by Stimulated Emission Radiation.

LED – Light Emitting Diode.

MOS – Metal oxide semiconductor.

CCD - Charge coupled device.

VIs – Virtual Instruments.

List of Figures

List of Tables

1 Introduction

The project that will be developed in this document consists on the integration of a laser scanner into a machine tool to obtain a 3D measurement from a freshly machined part. The project counted with a cooperation between the WZL and the manufacturers of the laser and the CNC machine.

The main interests for this project looks for new studies and knowledge about the insertion of a new kind of inspection that is able to measure parts dimensions inside the CNC machine.

The next following contents will explain in details the project objectives, the context and the institution where the project was built up.

1.1 RWTH and WZL

A cooperation between this institute and the automation department (DAS) at Federal University of Santa Catarina (UFSC) allows students to perform internships projects into RWTH University institutes. RWTH is worldwide recognized for its excellence in education and research in engineering. Within this context, the project was performed in the WZL institute.

The WZL, german acronym for laboratory for machine tools and production engineering, is an institute of the RWTH Aachen University. The institution represents a forward thinking research and innovator place for the new ideas in the field of production engineering.

In eight different working areas, the projects developed in this institution looks for not only fundamentals and theories, but also to improve and apply the fundaments of the academic field inside the industrial context.

This document is inserted into the metrology and quality management research area of WZL. The main objective of this area is to develop and optimize the measurement process by automating and integrating the measuring system in the industrial production.

1.2 Three Dimensional Metrology

As design geometries continue to shrink and materials become more complex, the new metrology methodologies needs to follow request and became better to achieve the new patterns complexity. In order to reach the goal, metrology became even more wide and started to look for not only measure small and simple objects, but also to measure and reconstruct complex objects models virtually .

The metrology field is big and have plenty of different solutions, because each application requests for a different measuring uncertainty and error. Sometimes the access to the environment is almost impossible, which causes difficulties to make a measurements with short constrains. These difficulties leads the metrology to be daily challenged to became more flexible and precise.

Every achievement of metrology was driven by challenges. One of the challenges of metrology was, to get good measurements without touching the measurand. The discovering of new technologies and new measurements principles, made possible the conquest of this challenge. That's why today we have a plenty of different ways, to measure any type of geometry and material in different environments.

In the metrology science, is possible to sort the measuring approaches into their measuring procedure. When the utilized procedure requires contact interaction between the measurand and the measuring device, this can be named as contact measurement. In the same way, when the measurand and the measuring device don't have contact interaction, this process is named as non-contact measurement.

As is possible to view in the Figure 1 the dimensional metrology have a lot of procedures to measure an object, but each of those procedures has their own fundament and their own application. The indicated (green arrow) classification represents the laser scanner measuring process, which is a non-contact procedure and allows measurement of delicate objects.

In an optical and active process, a light source radiate structured light into the measurand, and by using the optics fundaments of reflection, the light is reflected in the environment. Using an appropriated camera, the reflected light capture is possible, and also contains the object characteristics.

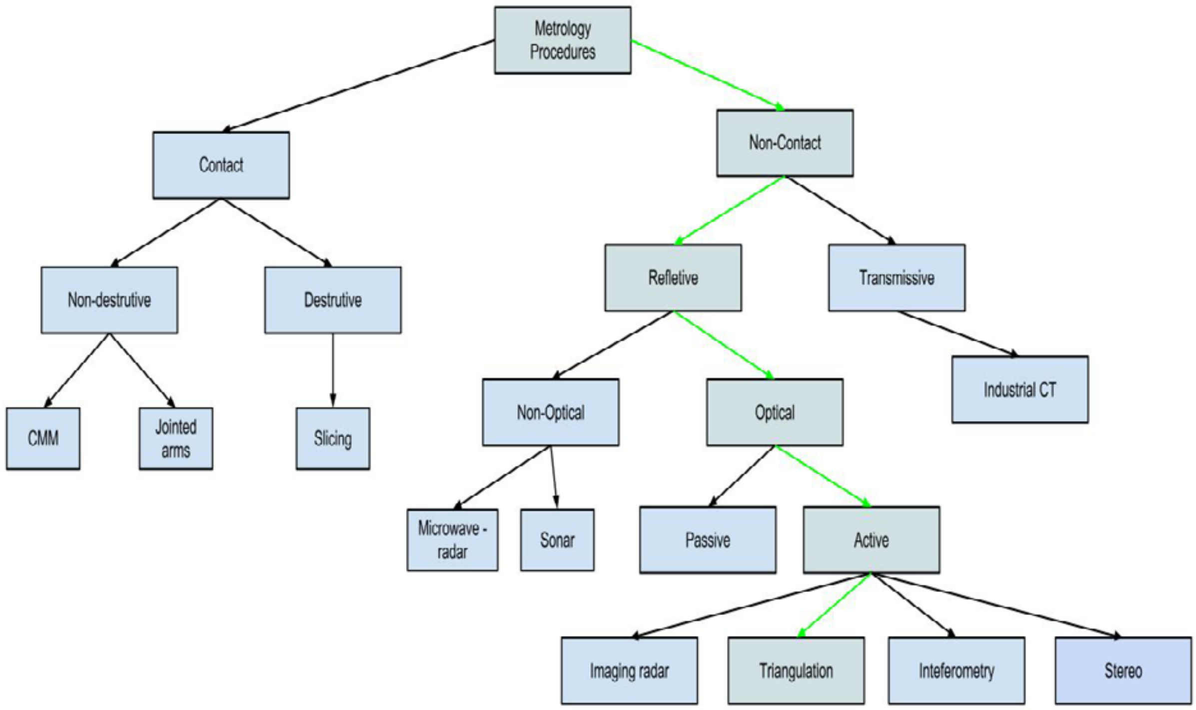


Figure 1 – Metrology procedures tree.

1.3 Work Objectives

First of all the project is an attempt to introduce a laser scanner inside a machine tool, with the purpose of scan objects freshly machined. As this is a new attempt, the main objective of this work is to analyze the chances of the integration between a laser scanner, for parts inspection. That will enable a measurement of geometric quality parameters inside the machine tool.

The inclusion of new sensors, aims an improvement of the measuring capabilities in the machine tool, in order to face the challenging inspection requirements of a dynamic small series production of large volume parts for example.

As this is a brand new project, nothing have been done before, so everything that was developed in this project is presented in this documentation. As normal, at the beginning lots of references were read, with the purpose of acquiring better understanding and knowledge of the devices and the technology involved in the laser scanner and the machine.

In addition to it, a research on data fusion tools and models were performed in order to, correlate and match 2D and 3D information acquired through the different sensor.

Including the sensor into the machine requests for some hardware integration. Looking to that, some hardware strategy to insert the laser scanner as a tool of the CNC machine also needs to be performed.

Not only that but also the software integration is necessary to perform a 3D reconstruction of the scanned object. The functionalities of the new sensing systems (image acquisition and processing) as well as, data fusion are also taken in consideration during the project development.

In short, the objectives and also the steps of this work are:

- Preliminary study of the actual sensors and machines.
- Establish a solution for the hardware integration.
- Establish a solution for data acquisition from the sensor and the machine.
- Obtain calibration and transformation matrix for data handling.
- Obtain a 3D model of free formed objects.

1.4 Document Structure.

The main goal of this work is to discover if, the possibility of the insertion of a laser scanner inside a CNC machine is viable. In the actual state of metrology most of this work will be focused in research and with great efforts make the integration happen.

In the chapter 2, a review of the science fundamentals and the technical background necessary for this work is presented. In this chapter we present a brief view inside the production metrology, which is the context where this project is inserted. After that, some technical fundaments of the measuring device, as the laser metrology and camera metrology is presented. And to finish this chapter a review in CNC machine basics and programing.

The chapter 3 presents to the reader, the machine and the laser scanner who were used for this project. The focus of this chapter is to show the hardware characteristics, geometry and the some special devices that were important for the realization of this integration work.

Chapter 4 covers all the integration work that were necessary to extract a virtual 3D model of the scanned object. In the beginning of the chapter is presented the hardware integration. That comprehends the introduction of the laser scanner inside the CNC machine. After, it’s presented the mathematical problem between the integration of the different coordinate systems. Ending chapter 4, the software integration shows how the data are acquired and treated, until the 3D model be built.

Chapter 5 brings up the results of this integration project. The scanned objects are showed and also a comparison between the real part and the virtual 3D model. To end this chapter is presented some calibration results.

Chapter 6 ends this document with the presentation of a personal synthesis of the results of the work. Here is showed the interpretation of the results. And to finish some glimpsed prospects for the project future are also presented.

2 State of the Art

In state of the art chapter, will be presented a review of the techniques and background knowledge for the development of this academic project.

This chapter starts with a quick discussion about the production metrology, which are the context where this study case is situated. After is also presented, some concepts as well as the camera metrology and the laser metrology that are the fundamentals for the construction of the measurement tool. It is also presented a fundamentation into the tool machine technology that is supposed to be integrated.

2.1 Production Metrology

Long years before the age of the industrialization, it was necessary to compare geometric sizes of different goods. Is true that the need of an accurate measurement in the old Egypt, were not so short as the limits for measurement in the post industrial revolution. The definition of a default measurement were not established, so the typical dimension were fingers widths, feet and steps. The result of this uncertain standard measurement system, causes problems for fitting and duplication.

Nowadays, the basics concepts for metrology must be uniquely defined, that is the reason why today most of the countries in the world uses SI-system of units. With this standard system, all the technical data can be understood and analyzed in different regions.

The production metrology is the generic term for all activities connected with measurement and testing functions to be provided in the industrial development process of a product. This global definition, results from changed production conditions, a high level of automation, short product life span, a reduced vertical range of manufacture and increased demands on product quality. These aspects form the functions and objectives of production metrology. It is developed from being a pure checking procedure to an important component of quality management. [1]

The most common test within production metrology, with a proportion of 90%, is the geometric testing of workpiece properties. In addition to the measurement of shape, mass or location of geometric elements, surface texture is often also an important workpiece component for the operational efficiency of a future product. [1]

The field of production metrology is not constrained to measurement and testing procedures. Production metrology faces new challenges, which nowadays are characterized by a high level of automation, short product life span and declining vertical range of manufacture.

In order to help the reader understand the technical terms of metrology, which will be used during the development of this project, the table 1 is presented.

Measurand	Is physical quantity subject to measurement.
Measurement	Is the execution of planned operations to quantitatively compare the measurand with a unit.
Counting	Is the determination of the value of the measurand “number of items in a quantity”.
Testing	Means establishing to what extent a unit fulfills a demand.
Measurement result	Refers to the estimated value of the true value of a measurand, which is gained from measurements.
Measuring device	Is an instrument, which is intended to measure a measurand, either on its own or in connection with other mechanisms.
Calibration	Determines the relationship between the measured or expectation value of the output quantity and the appropriate true or correct value of the existing measurand available as the output quantity, for a measuring device under given conditions.
Adjustment	Is the positioning or alignment of a measuring device, in order to eliminate systematic measurement deviations as much as possible, to the extent that it is necessary for the intended measurement.
Measurement principle	Is the physical basis of the measurement.

Measurement method	Is a special type of procedure for measurement, which is independent from the measurement principle.
Measuring procedure	Defines the practical application of a measurement principle and a measuring method.
Correct value	Is recognized by agreement and assigned to a particular quantity with an uncertainty appropriate for the respective purpose.
Measurement uncertainty	Is a parameter associated with the result of a measurement that characterizes the dispersion of values which could reasonably be attributed to the measurand.
Measurement error	Is the deviation from the true value of a value gained from measurements and assigned to the measurand, or the measurement result minus the true value of the measurand.

Table 1 – Metrology terms definition. [3]

2.2 Measurement Device Fundamentals

In this section will be discussed the main subjects that makes real the conception of a laser scanner. All of the scanning process, since the creation from the laser light until the computer receives the data, is possible thanks to this issues that will be explained in the next subchapters.

2.2.1 Camera Metrology

In the last decades, the camera metrology has gained in importance more than many other measuring procedures. This is justified, by the high level of flexibility and processing speed of the systems which has taken the rapid development of computer technology in its wake. On the other hand, measurement or inspection using a camera image represents a technology which strongly accommodates human perception and therefore makes it suitable for many industrial tasks.

The Figure 2 shows the instruments used in the camera metrology. The images are recorded by the camera, and by the use of a frame grabber the images are treated and transferred. The computer as a final stage is used for the all the image processing.

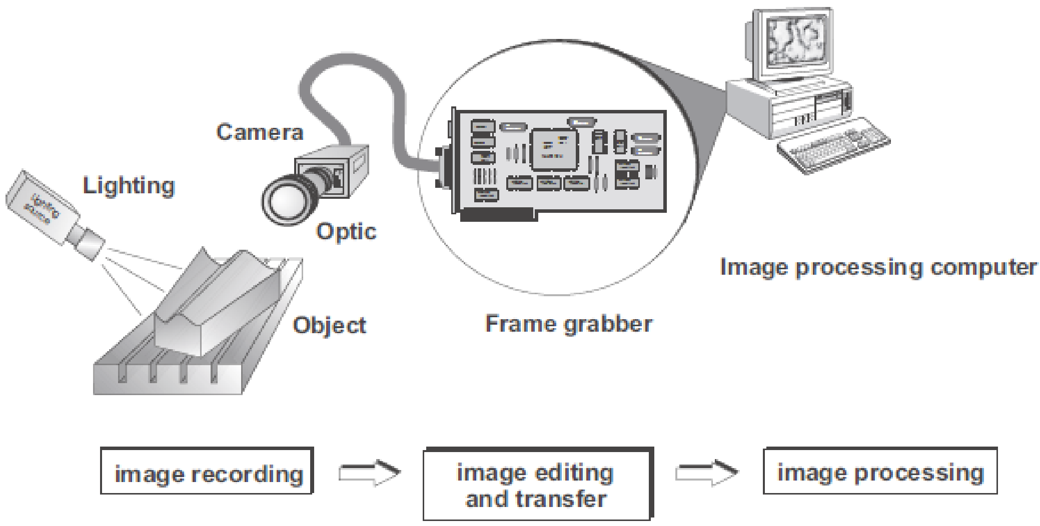


Figure 2 - Fundamental components and steps for camera metrology. [1]

2.2.1.1 Mirrors

Mirrors are primarily used if a modification is required in the direction of light beam paths. These reflect the light, such that the angle of the reflected light corresponds to that of the incident light, for instance $\alpha1=\alpha2$ applies.[1] The uses of the mirrors into this project are explained into the 3.1.3 subchapter.

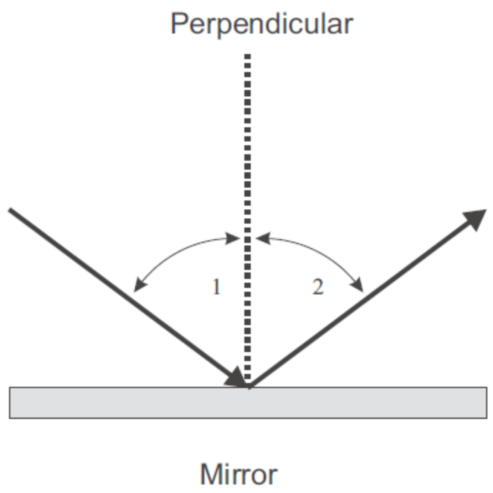


Figure 3 – Schematic representation of a mirror.

2.2.1.2 Lenses

Lenses are an important part of most optical systems. Good results in optical measurements often rely on the best selection of lenses. [8]

Lenses are an optical device responsible for transmit and refract light, by converging or diverging the beam. There are six main types of lens (Figure 4), each one with a different geometry and a different proposal. Lenses are classified by the curvature of the two optical surfaces.

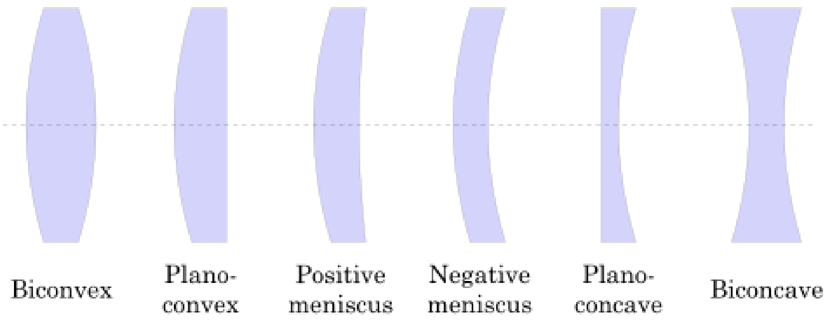


Figure 4 - Lens types.

In the Figure 5, the function of a convergent and a divergent lenses is reported. A converging lens is the one which causes rays that enter it traveling parallel to the axis to converge toward the axis after refraction.

A diverging lens is the one which causes rays that enter it traveling parallel to the axis to diverge away from the axis after refraction. diverging if it is negative. [9]

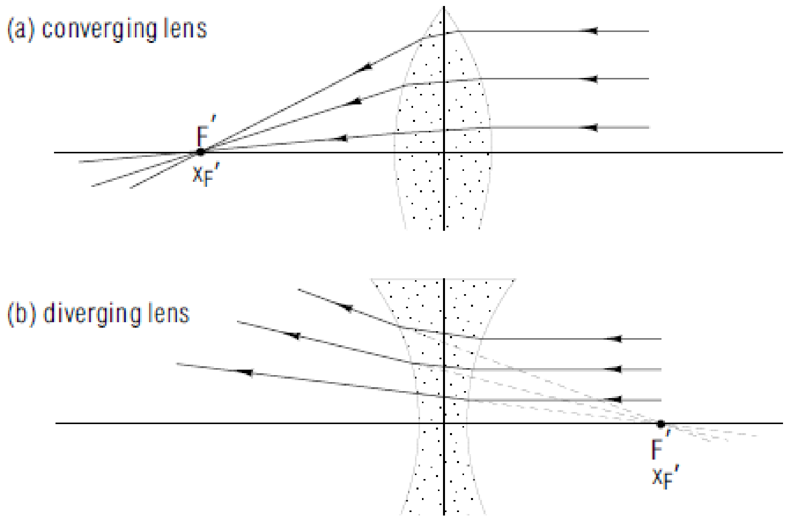


Figure 5 - Converging and diverging lens. [9]

The thin lenses equation 1 , that is also called “Gaussian form of the thin lens equation”, is probably the most used equation in the optics.

$$\frac{1}{xF} = \frac{1}{x_0} - \frac{1}{x_i} \qquad (1)$$

Where: xF = focal length.

x_0 = x position of object.

x_i = x position of the image.

To discover the focal length of a lens the equation 2 is presented.

$$\frac{1}{xF} = (n-1)\left(\frac{1}{xC_2} - \frac{1}{xC_1}\right) \qquad (2)$$

Where: n = index of refraction of the lens.

xC_1 = x position of the center of curvature of the first lens.

xC_2= x position of the center of curvature of the second lens.

2.2.1.3 The Photodiodes

The photodiode is a semi-conductor component. Their operational principle is based on the absorption of light in the p-n junction which leads to a generation of pairs of electrons (p-n photodiode). In the case of external short circuits or with adjacent reverse voltage, the electric field in the p-n junction splits electrons and holes from one another before a noticeable recombination can take place, thus increasing the cut-off current. This increase in cut-off current depends on the intensity of the incident light.

The efficiency can be improved if an undoped (intrinsic) intermediate layer (pin photodiode, Figure 6 a) is inserted between the ‘p’ and ‘n’ doped areas. This permits more light to be absorbed. A further efficiency increase can be achieved by such a large pre-loading of the pin diode in the reverse bias that the optically produced electrons and holes cause impact ionization on their way through the i-zone, thus releasing an avalanche of charge carriers (avalanche photodiode, Figure 6 b). [1]

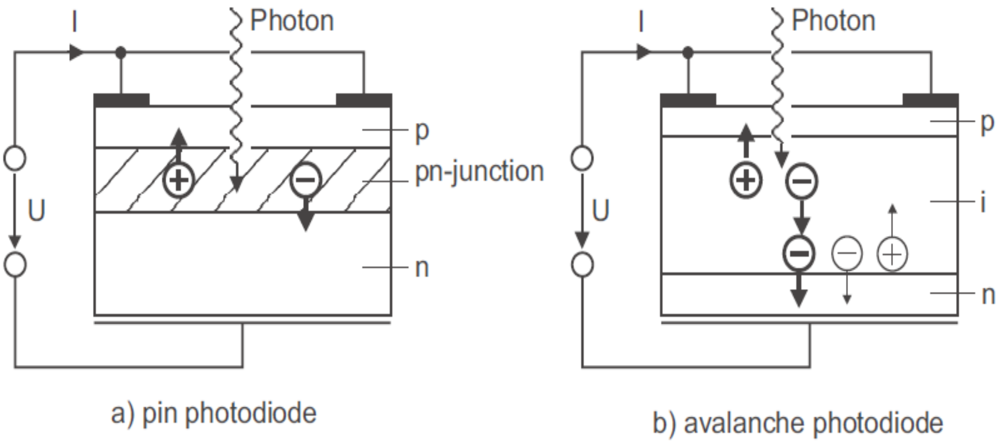


Figure 6 - Types of photodiodes. [1]

2.2.1.4 CCD Image Sensor and CCD Cameras.

The core component in all types of scanners is the CCD chip array. The CCD is the most common technology for image capture in scanners. CCD is a collection of tiny light-sensitive diodes, which convert photons (light) into electrons (electrical charge).

In other words a CCD image sensor consist of a matrix arrangement of partially more than 10^6 MOS capacitors, where each one represents an individual pixel from an image. The MOS capacitor, as is presented in the Figure 7, consists of a p-doped silicon layer, an insulator layer and an electrode.

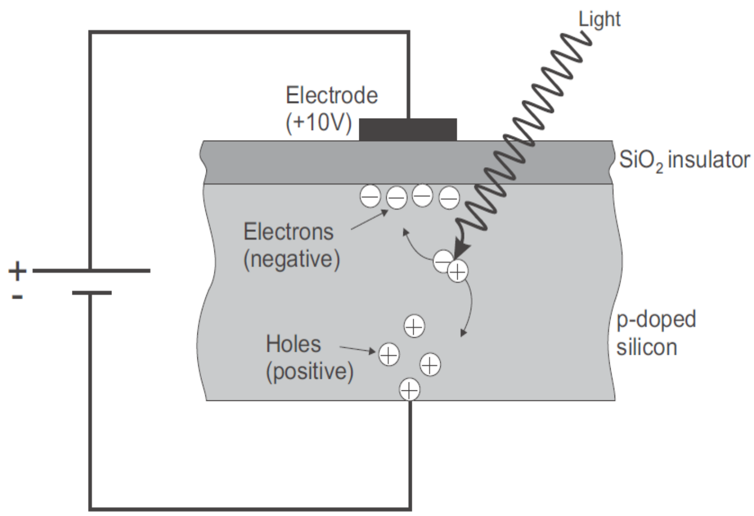


Figure 7 - Structure of an MOS capacitor. [1]

Light which meets the p-doped substrate produces pairs of electrons, the number of which depend on the strength and duration of exposure (integration time). As the initial potential of the electrode is maintained at approx. +10 V, a charge separation takes place. The positively charge holes are repelled by the electrode and flow off to the mass, while the negatively charged electrons are drawn to the electrode. They do not, however, reach the electrode, but are stopped by the insulator layer and accumulate under the electrode. Their number is a direct measure for the local exposure in the observed pixel. [1]

The exposure information of each electron in an individual pixel, is picked by the use of a charge coupled transport system named CCD. Using a setting of voltage systematic, the accumulated electrons are shifted from one electrode to the next, until they finally reach the output level. After this, those electrode information are converted in a voltage signal that can be used as a video signal.

The operation of the charge couple transport system is represented exemplarily in Figure 8. First a voltage is only set on Electrode A, under which several electrons have accumulated due to the influence of light. Now, the same voltage is set on the neighboring electrode B, so that the electrons distribute themselves evenly under electrodes A and B. Subsequently, electrode A is placed on mass, through which all charges which were initially under electrode A, now move under electrode B. Thus a charge transfer of one electrode to a neighboring one has taken place, which is repeated until all charges have been selected. The degree of efficiency of the charge transfer is between 99.99% and 99.9999%, so that the charge transfer taking place is essentially free of loss. The shifting of charges from one electrode to a neighboring one takes approx. 60 ns, this means, for instance, that every 60 ns a pixel is selected at the video output. If the pixels are arranged in lines or in matrix form, the result is a light-sensitive CCD chip, which represents the basic element of a CCD line or CCD matrix camera. The light sensitive pixels arranged in a uniform grid have a typical size of 8 – 13 μm.[2]

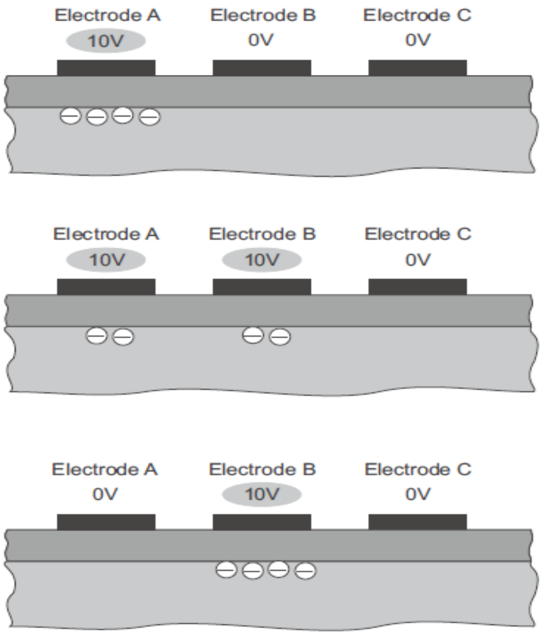


Figure 8 – The charge coupled transport. [1]

In the Figure 9 is showed the structure of a CCD camera chip, where the image is electronically captured for a posteriorly reconstruction. The CCD chip have several columns, every white cell have a dark cell in his side, that together form a basic cell. The white cell is the one who is optically sensitive to light and also represent one pixel of the image. The black cell, is an additional cell responsible for the charge transfer of every light-sensitive pixel cell, in other words it is an analog shift register, called CCD bucket chain.

After the integration period the pixels, in the white column, are charged and a then theses charge are shifted to the black cell were the pixels are temporarily stored. After the individual charges of each pixels are changed into a output voltage by a selection diode. This voltage are cyclically sent, as voltage pulses, that is changed into a continuous signal through a Sample-Hold member. This analog signal is an input to an interface card, where the this signal can be digitalized and stored in the memory.

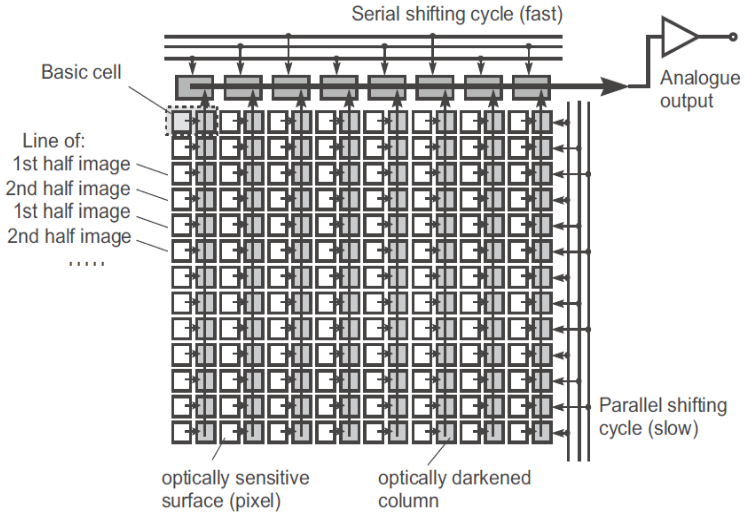


Figure 9 – Structure of a CCD camera chip. [1]

2.2.2 Laser Metrology

It is clear that not today but also in the near future, the requirement for fast precision and highly exact geometrical measuring of a wide variety parts will be necessary for achieving better results in the parts fabrication. This growing demand will be satisfied with the improvements in the field of automation. The laser technology is being applied constantly in the field of metrology thanks to the advances in electronic and optics. Today the laser metrology makes possible quick and flexible the quality inspection in industrial applications.

2.2.2.1 The Laser Technology

In the last years laser technology is growing and getting more and more sophisticated. The laser light is being used in different areas and applications. Today we can see the laser technology being applied in medical offices, metrology as well as in the heavy industries. In medical applications the laser beam is extensively used in the ophthalmology , cellular sorting and vision correction. High-power lasers have been used for cutting and welding materials. Today the frames of automobiles are assembled using laser welding robots, complex cardboard boxes are made with laser-cut dies, and lasers are routinely used to engrave numbers and codes on a wide variety of products. Some less well-known applications include three-dimensional stereo lithography and photolithography Scanning Procedures. [2]

In the metrology area, the laser is been used for non-contact inspections, after the manufacturing. The laser beam, scans the manufactured piece searching for cracks or geometric errors. In the end of the scan process is possible, thanks to the software advances, to get a virtual copy from the piece, where all the data withdraw from the piece can be stored and analyzed.

In the modern laser metrology, there are lots of ways to acquire data from the part geometry. Every procedure have their advantages and also limitations. In the following subchapter more about this procedures are presented.

2.2.2.2 3D Laser Metrology

In the 3D optical metrology goal of the measurement is to extract form the scanned measurand, his geometry. By extracting the geometry in 3D, it means getting the shape of the measurand in the form of coordinates X, Y, Z in a cartesian system.

Today to rebuilt a workpice it is possible to use 3 different types of optical sensors. The difference of these sensors, is the way that you get the data from the scanned surface. The type sensors are showed in the Table 2.

Sensor	**REQUIREMENT**	**PROCEDURE**
1D	2 external axes movement for a 3D measure	Triangulation
		Time to flight
		Interferometry
		Holographic
		Focus
2D	1 external axis movement for	Triangulation
		Interferometry

	a 3D measure	Focus
		Microscopic
3D	No need for movement.	Triangulation
		Interferometry

Table 2 – 3D scanning sensors and procedures.

The 1D sensor provided data in the one dimension, in other words he provides points. So in order to get a 3 dimension part, it is required to move the scanner in two different axes. In the case of a 2D sensor the provided data is a line, that makes the require of move in one axis. With a 3D sensor the result of the measurement allows the reconstruction of a part without movement in the axis.

More about the most used procedures will be presented in the next subchapters.

2.2.2.3 Triangulation Procedure

Laser triangulation procedure is based on the projection of a laser over an object and the reflected stripes are captured by a camera. The triangulation measuring principle is based on the determining of the side of a triangle by determining two triangular angles while knowing the length of the triangle side included by the Figure 10.

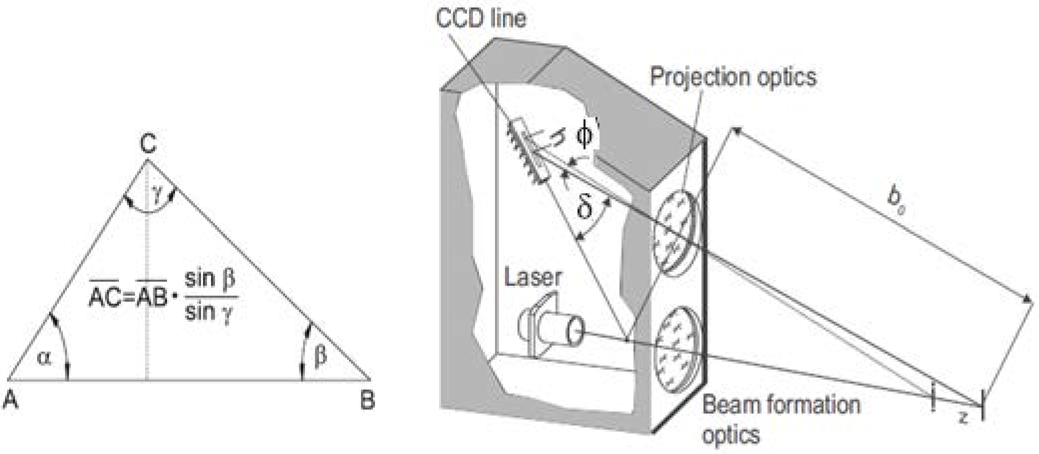


Figure 10 - The triangulation principle and the structure of a triangulation sensor. [1]

If the distance from the laser source until the camera, and the length of the segment AB, is known, the distance AC can be determined by measuring the angles α and γ and some trigonometric calculations. With the technical realization of a laser triangulation sensor, the light from an appropriate laser source is focused on the workpiece surface through beam forming optics and the resulting point of light is displayed on a position detector.

If the distance of the measured workpiece surface changes, the display position of the projected light point also changes on the detector, the length of which limits the measuring range. In order to avoid an unfocused display of the measuring light point on the detector, which is caused by the change in the representation ratio within the measuring range, the line detector must be arranged according to the Scheimpflug principle. [1]

The detector is inclined at the angle δ, so that the beam axis of the light source, the level of the representative optics and the detector level intersect at one point.

A Δz shift of the measured object from the base distance along the light beam axis leads to a shift of distance Δh by the measuring mark displayed on the detector. [11]

$$\Delta h = b_0 . \frac{\sin(\phi)}{\sin(\delta - \phi)} \qquad (3)$$

With laser triangulation, the attainable measurement uncertainty depends on the surface texture of the sample. With an ideally diffusely dispersed surface, a Gaussian distribution of light intensity results on the line detector. The better the intensity distribution on the line detector (correlated with the ideal Gaussian distribution) the lower the influence of the surface on the measurement uncertainty. With surfaces which indicate diffuse reflective characteristics such as paper or ceramics, a very low measurement uncertainty can be attained. With strongly reflective surfaces, here metallic surfaces with very little roughness can be included and surfaces which the laser beam penetrates, such as various plastics or glass, the surfaces substantially influence measurement uncertainty. Furthermore, attention must be given that the workpiece does not creating shadowing of the transmission and reception beams. [1]

2.2.2.4 Interferometric Procedure

Laser interferometer applications include some of the world's most accurate length and distance measurement equipment. The interferometric procedure is widely used in engineering, physics and astronomy. The description of the basic principles of interferometry are grounded on the Michelson interferometer structure(Figure 11).

Interferometry makes use of the principle of superposition to combine waves in a way that will cause the result of their combination to have some meaningful property that is diagnostic of the original state of the waves. This works because when two waves with the same frequency combine, the resulting pattern is determined by the phase difference between the two waves that are in phase will undergo constructive interference while waves that are out of phase will undergo destructive interference. Most interferometers use light or some other form of electromagnetic wave.[4]

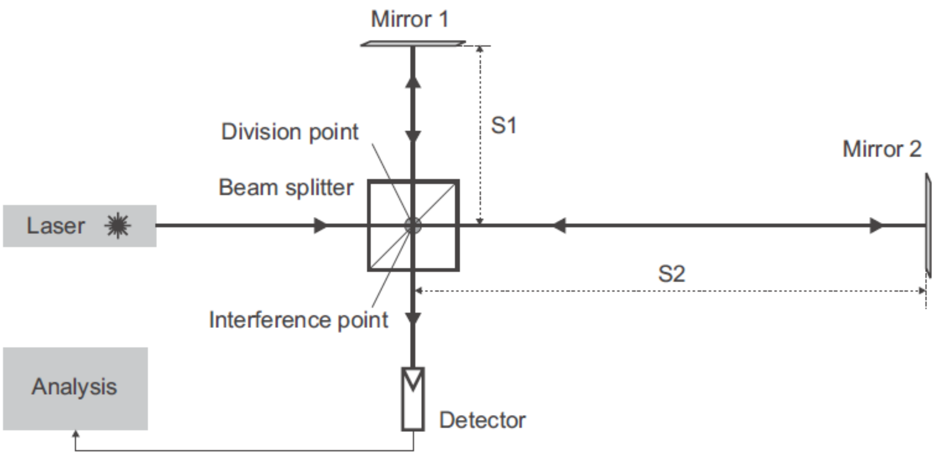


Figure 11 - Structure of a Michelson interferometer. [1]

The outgoing light from the laser is divided up by the beam splitter. The resulting partial waves are reflected by mirrors after passing through the paths s1 or s2. After both partial beams have passed through the respective paths again, they are overlaid behind the point of interference. Depending on the relative phase position of the partial waves, an intensity is registered between a maximum value and almost complete cancellation.[1]

For the mathematical description of all the interferometric procedure we recommend the reading of the reference [1].

In order to obtain information about a scan object the interfermotric procedure were improved by Twyman-Green. His solution is presented in the Figure 12.

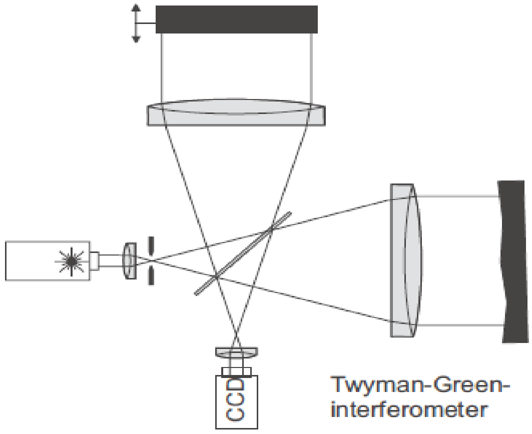


Figure 12 – Principle of form testing interferometer according Twyman-Green. [1]

In Twyman-Green interferometers, the reference and measuring arms are spatially separated from one another. In order to achieve this, a beam splitter is used which divides the wave front in the intensity ratio 50:50. Both partial wave fronts are collimated in each case with optics. While the reference wave front is reflected back in itself without modifying the phase by a precision flat mirror functioning as a reference, the measuring wave front impacts the test piece. With the reflection at the test piece, the profile of measuring wave front is now, as it were, impressed to the measuring wave front. A modification of the originally constant phase φ of the measuring wave front into a distribution φ(x,y) is the consequence. The information about the height profile z(x,y) of the test piece is thus contained in this phase distribution.

The distorted measuring wave front formed in such a way interferes with the reflected reference wave front after their overlay at the beam splitter and an interferogram is developed.[1]

2.2.2.5 Time of Flight Procedure

Time of flight procedure is well used for distance measurement and large measurement segments. In this procedure is measured the time which an amplitude modulated luminous laser beam requires to pass through a measurement segment and back. With the knowledge of the speed of the light and this measured time, is possible to calculate the travelled distance of the laser beam.

The laser is used to emit a pulse of light, so the beam of light focus in the workpiece, that reflects part of the light to the range laser that captures the time of the journey from to moment of the emission until the capture of the reflected beam (Figure 13).

Since the light speed is ***c*** and the captured round trip time is ***t*** the distance is calculate by the equation 3 :

$$D = \frac{c.t}{2} \qquad (4)$$

The measuring range of the travel time procedure reaches from 0.2m to 1 km and permits a resolution of approximately 1 mm. It is, however, at times heavily impaired by environmental influences (such as air pollution or object surface). Typical fields of application are positional, distance or fluid level measurements, but 3D surface recording systems can also be realized through the application of movable reflecting mirrors. [1]

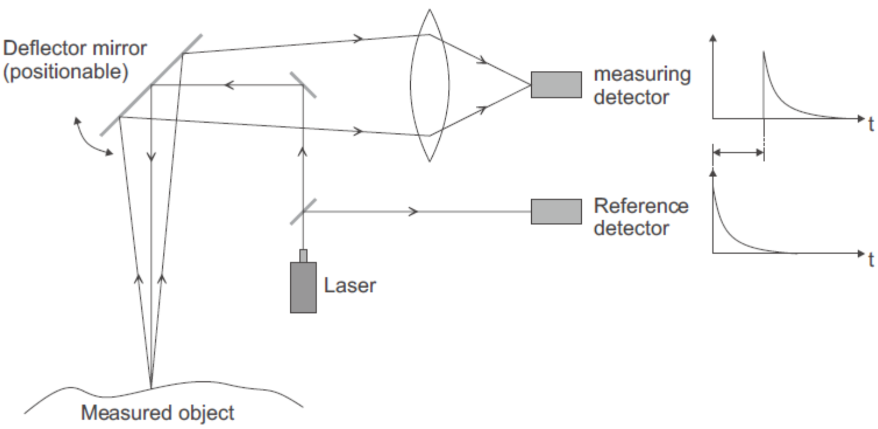


Figure 13 – Time of flight procedure. [1]

2.3 Machine Tool Fundamentals

The first NC machines were built in the 1940s and 1950s, based on existing tools that were modified with motors that moved the controls to follow points fed into the system on punched tape. These mechanisms were improved with analog and digital computers that results in the creation of the modern computer numerical control (CNC) machine tools, that have revolutionized the machining processes. In recent decades these machines were the subject of many technological advances in the field of the automation.

These new advances, brought the conception of the computer-aided design (CAD) and computer-aided manufacturing (CAM) programing. These two programs generates computer files that when interpreted, generate the commands needed to operate single machine processor, and then loaded into the CNC machines for the parts production.

2.3.1 The overview of a Computerized Numerical Control Machine.

In the present configuration of the state of art, the CNC machine are well developed and have the same configuration as the Figure 14 shows.

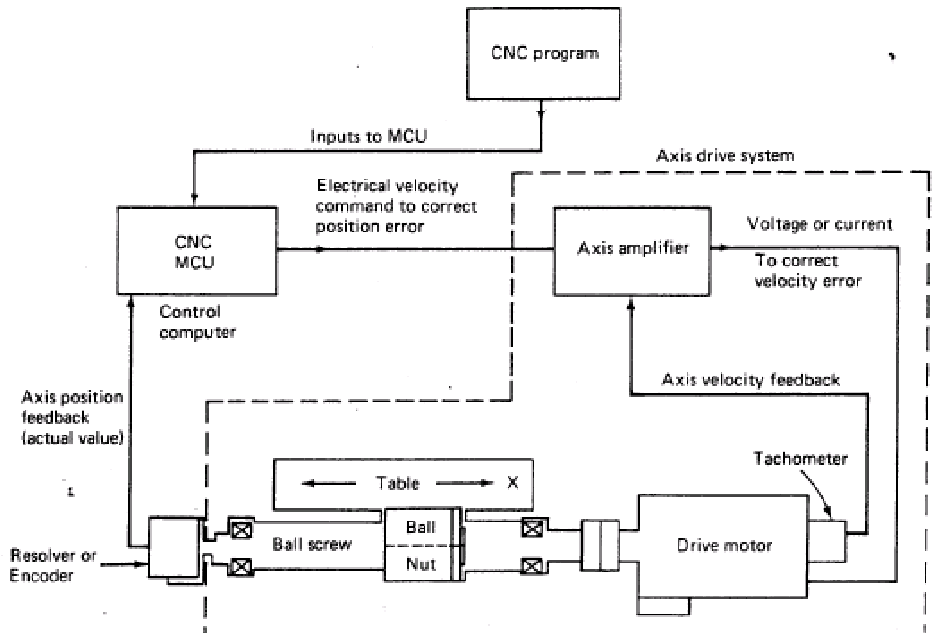


Figure 14 – CNC overview.

All procedures for a CNC machining begins with a part program, which is a sequential instructions or coded commands that direct the specific machine functions, normally written in G code. This part program may be manually generated or, more commonly, generated by computer aided part programming systems as CAD/CAM modeling software.

The part program is passed to the CNC and interpreted by the MCU(machine control unit). In this CNC code the programmer decides, according to the material and the desired geometry for the part, the cutting speed, feed, depth of cut, tool selection, coolant on off and tool paths. The MCU issues commands in form of numeric data to motors that position slides and tool accordingly.

This programmed instructions are converted into output signals which, controls machine operations such as spindle speeds, tool selection, tool movement, and cutting fluid flow.

All computer controlled machines are able to accurately and repeatedly control motion in various directions. Each of these directions of motion is called an axis.

Additionally, a CNC axis may be either a linear axis in which movement is in a straight line, or a rotary axis with motion following a circular path.

2.3.2 CNC Motion.

The motion control is the main function of any CNC machine. With the an automatic motion control the machine reach the target point in a consistent, quick and precise way.

Normally the most of actual CNC machines have three to five axes. Each axis consists of a mechanical component, such as a slide that moves, a servo drive motor that powers the mechanical movement, and a ball screw to transfer the power from the servo drive motor to the mechanical component. These components, along with the computer controls that govern them, are referred to as an axis drive system.

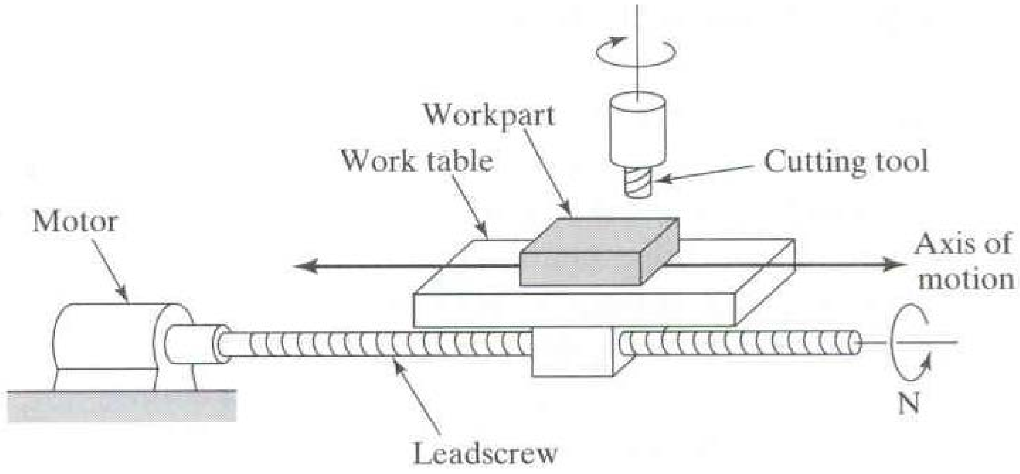


Figure 15 - The components of an axis motion.

2.3.2.1 The Mechanical Linear Actuator.

A linear actuator is an actuator that creates motion in a straight line, as contrasted with circular motion of a conventional electric motor. Linear actuators are used in machine tools and industrial machinery, in computer peripherals such as disk drives and printers, in valves and dampers, and in many other places where linear motion is required.

For each one of the axis an electro-mechanical linear actuator is responsible to move the tool to a desired point in the machine work field. The linear actuator used in the actual CNC machines typically operate by converting a rotary motion into linear motion. In other words for an CNC machine the linear actuator transfer and convert the rotating motion from the motor, destined to generate power for one axis, to a linear displacement in the corresponding axis. There are different solutions for the construction of this mechanism, such as screw, wheel an axle and cam.

For this documents we will describe the most common type of screws used in industrial machinery and precision machines, that is the ball screw.

2.3.2.1.1 The Ball Screw.

The primary function of a ball screw, as told before, is to convert rotary motion to linear motion or torque to thrust, and vice versa, with the features of high accuracy, reversibility and efficiency. As a result from this conversion this mechanism is also responsible for transmit forces and for, in the CNC machine case, moving the tool or the table.

Ballscrews, also called as ball bearing screws, recirculating ballscrews, consist of a screw spindle and a nut integrated with balls and a return mechanism for balls, return tubes or return caps. As is showed in the Figure 16.

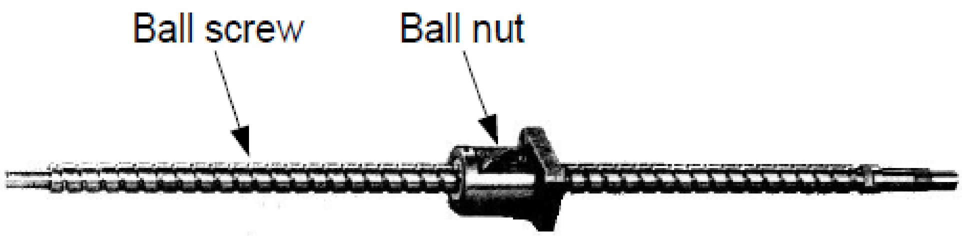


Figure 16 - The ball screw. [6]

There are three different configurations for recirculation of the balls, as presented in the next subsections.

2.3.2.1.1.1 External Recirculation Ballscrew.

The first design is called external recirculation type ballscrew, consists of the screw spindle, the ball nut, the steel balls, the return tubes and the fixing plate. The steel balls are introduced into the space between the screw spindle and the ball nut. The balls are diverted from the balltrack and carried back by the ball guide return tube form a loop. Since the return tubes are located outside the nut body. [7]

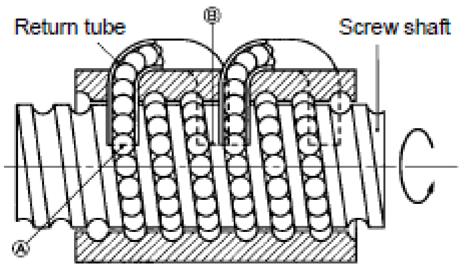


Figure 17 - External ballscrew. [6]

2.3.2.1.1.2 Internal Recirculation Ballscrew.

The second design, called the internal recirculation type ballscrew, consists of the screw spindle, the ball nut, the steel balls and the ball return caps. The balls make only one revolution around the screw spindle. The circuit is closed by a ball return cap in the nut allowing the balls to cross over adjacent ball tracks. Since the ball return caps are located inside the nut body. [7]

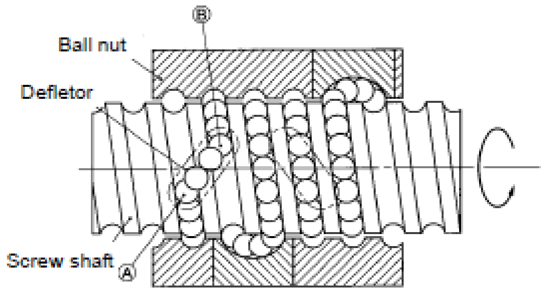


Figure 18 - Internal ballscrew. [6]

2.3.2.1.1.3 Endcap Recirculation Ballscrew

The third design is called endcap recirculation type ball screw. The basic design of this return system is the same as the external recirculation. Except that the return tube is made inside the nut body as a through hole. The balls in this design traverse the whole circuit of the balltracks within the nut length. Therefore, a short nut with the same load capacity as the conventional design can be used. [7]

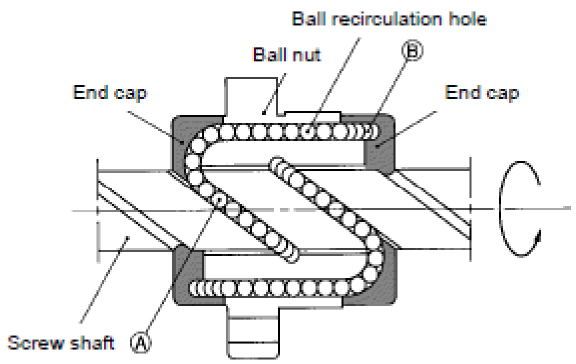


Figure 19 - Recirculation ballscrew. [6]

2.3.3 The CNC Machine Control.

Basically the CNC machine control, is responsible for execution of the commands gived as an input in the code G. The CNC machine control read the G command lines and control the servo motor to make the right movement in the axes with the specified speed and tool.

There are two different approaches to make this axes motion control:

The motor receive an input from the main control, that translate the G code to an appropriated signal, who can be read, processed and executed by the stepping motor. The approach is called an open control loop, as is showed in the Figure 20.

In a stepper motor, the input command specifies the desired angle of rotation, and the controller provides the corresponding sequence of commutations without the use of any feedback about the position of the system being driven.

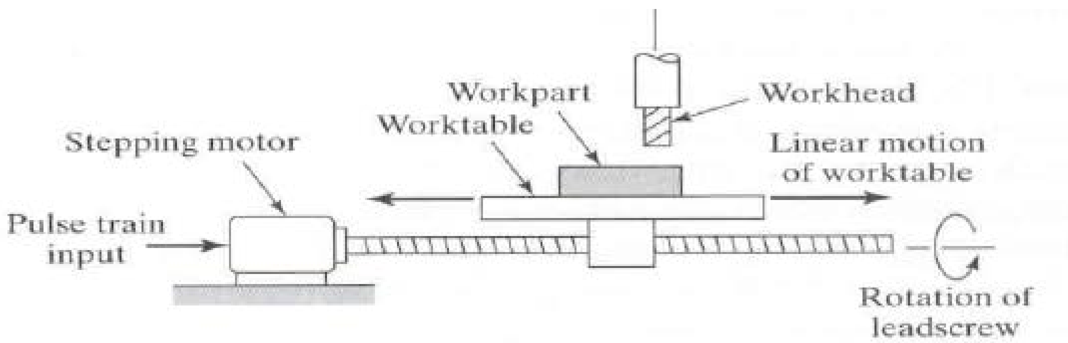


Figure 20 – Open loop control.

The second approach is the most used in the automatic and programed tasks works. The name of this closed loop control.

In the Figure 21 is possible to view that now in this new control, two important things for the construction of closed loop, were added in the control loop. An optical encoder, who is in charge to make the measurement of the actual position of the axis. The another element is the comparator, who basically by receiving the measurement signal from the encoder and the reference input, and get the difference between the desired position and the actual position.

The function of the DAC element is to convert the digital signal received from the control and pass to the servomotor as an analog signal with the length of the next step.

These last approach can also be called an feedback control system. This different control ways can be employed in the control of the position of the axes, in the control of the speed as in another tasks.

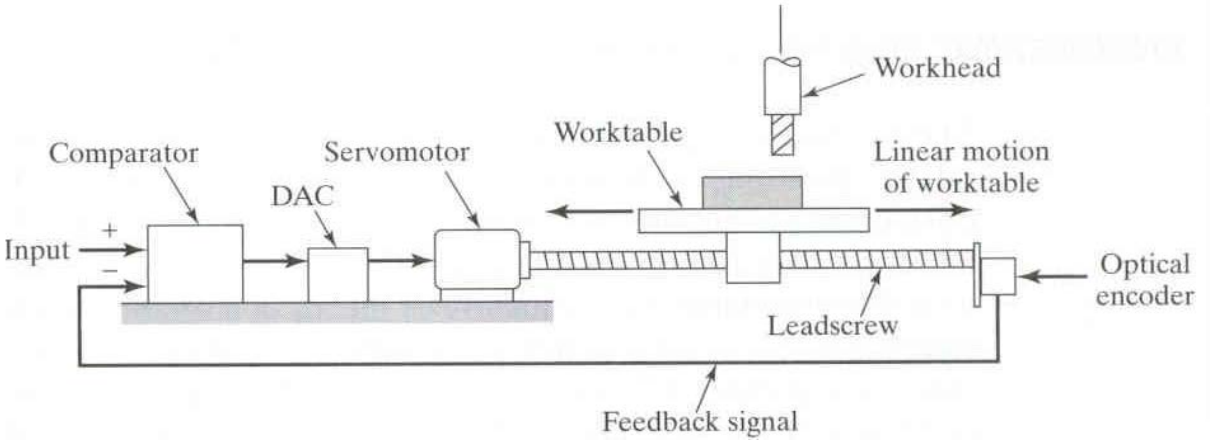


Figure 21 – The servo motor control system.

2.3.4 The CNC Programing.

The principal input to make the CNC machine work property, is the part code. The common languages of CNC machine programming is the code G or M. In this subchapter is presented a small and quick tutorial of how is made a CNC code in G code.

First it’s important to take a look in witch coordinate system, unit, are you planning to work. After, depending on the application and the material that do you want to work, you need to set another parameter as, speed rate, spindle speed and tool.

As the other languages programming, G code also consists of a series of instructions in form of letter codes. There are also a miscellaneous with M code that is often used in a CNC program.

In the Table 3 is presented the frequently used function in a CNC program.

Code	Function	Example
G00	Rapid linear move	G00 X20 Y10 Z200 (X,Y,Z = position)
G01	Feed linear move	G01 F80 X20 Y10 Z200 (F=feedrate to move at)
G02	Circular move Clockwise	G02 X20 Y10 R±2 (R=size of radius arc to swing. R+ if radius < 180°, R- if radius is > 180°)
G03	Circular move Counter clockwise	G03 X20 Y10 R±2 (R=size of radius arc to swing. R+ if radius < 180°, R- if radius is > 180°)
G54	Work coordinate shift	G54 X10 Y20 Z300 (Go to this XYZ position referenced from WCS)
M00	Program stop	M00
M03	Start the spindle in the forward direction (CW).	M03
M04	Start the spindle in the reverse direction (CCW).	M04
M05	Stop the spindle / Spindle off.	M05
M06	Tool change command	M06
M08	Coolant on flood	M08
M09	Coolant off	M09

Table 3 – Some G and M codes.

3 Hardware Devices Description

In this chapter it will be presented the laser scanner and the machine tool that were used during the development of the project. Some special conditions and the equipment necessary for a better approaching to the problem solution.

3.1 Laser Scanner

The laser scanner used in the project development is equipped with a 2D sensor, made in Germany by Nokra Optische Prüftechnik und Automation GmbH. The measurement method, has already been explained in chapter 2.2.2, triangulation method. Where the projected laser stripes interact with the measurand and by reflected beam light that reaches the CCD camera is possible to get the shape of the measurand.

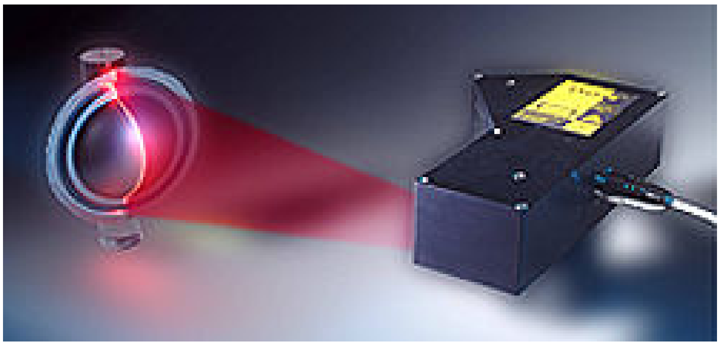


Figure 22 – Nokra Taglio

3.1.1 Characteristics

The Nokra laser is connected to a dedicated computer that runs on a Linux operating system. This system allows to run the laser software to parameterize and control the sensor. The communication with the sensor is based on the TCP/IP-protocol. All the sensor control and data acquisition takes place via an Ethernet interface.

In order to explain how the laser scanner works in this subchapter we will list the main equipment and explain their functionality in the scanning process.

The following equipment are essential for the construction of a laser scanner :

- Laser diode.
- Lens.
- Laser stripe

3.1.2 Laser Emitting Diode

A laser emitting diode (LED) is a semiconductor device, that converts electrical energy into the energy of optical radiation by making use of the phenomenon of injection electroluminescence in a semiconductor crystal with a p-n junction, a semiconductor heterojunction, or a metal-semiconductor contact. When a direct or alternating current flows in an LED into the semiconductor region adjacent to such a junction or contact, LED's emit radiation that is incoherent but has a narrower spectrum than that of thermal light sources. The radiation in the visible region is consequently perceived as monochromatic. The color of the radiation depends on the semiconductor material and its doping. Depending on the material and on wavelength used, the color can be visible or infrared. [13]

Nokra scanner uses a visible laser diode, with a wavelength between 650 nm 780 nm.

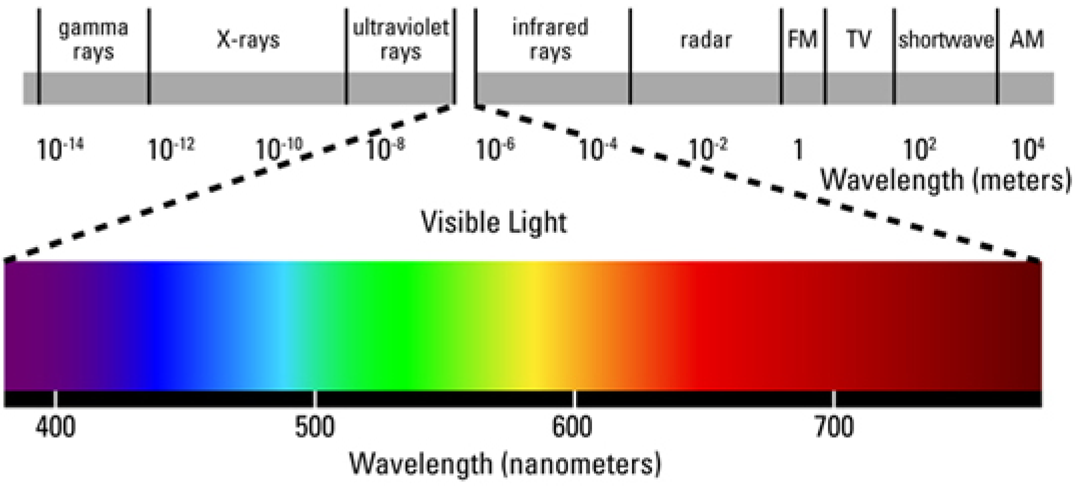


Figure 23 – Led colors and wavelength. [14]

Scanning systems often require bright and homogeneous illumination, in a small dispositive source of light. Due to their size, performance, and beam quality, diode lasers, constitutes almost an ideal source of light for the scanning procedure due to this sensor requirements.

The acquisition of the data from the scanned part surface, is just possible thanks to the characteristics from this light source. By using this illumination system and a good capture sensor, metrology can work with short and tight restrictions in a non-contact procedure.

3.1.3 Mirror and Lens

Taking into account that the led provide just a light point and the objective is a stripe, some modification needs to be done. So the mirror function, in this laser scanner, is to make a line with light points provided by the led. The mirror oscillates in high frequencies in order to reflect points in and make it into line form.

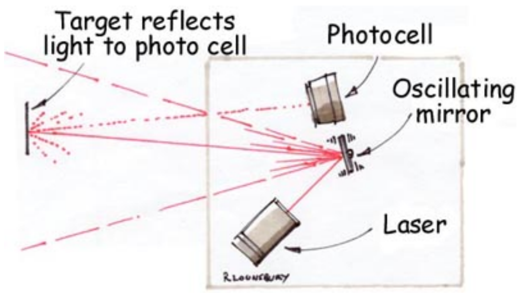


Figure 24 – Oscillating mirror.[16]

The lens are the part responsible for treating the laser beam right after his emission and before the camera capture. Lens are used as an optical filter against the light diffusion and deformation. There are two main lens in this laser scanner, the projection lens and the collecting lens (Figure 25).

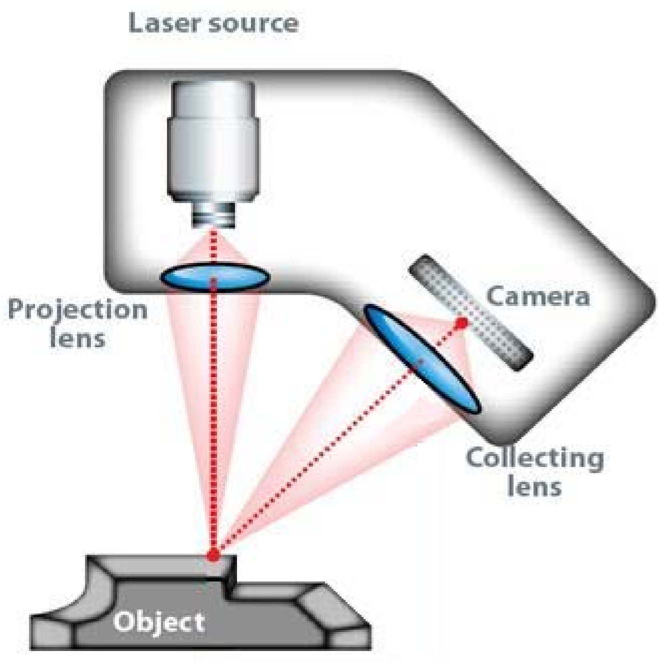


Figure 25 – Laser scanner lens.

The main objective of the projection lens is to receive the led beam and to project a line with the desired number of points on the object surface. In this case of lens, the most used type is the cylindrical lens or concave lens. In this lens the laser beam is receiving a line and projecting a larger line in the form of a cone.

The collecting lens do the opposite, they take the reflected and random type of beam and make it a parallel beam that reaches the CDD camera. So, the received laser stripe can be recorded as image with lots of points in the object shape. The most used lens for this application is the concave lens.

Depending on the lens that are used the working distance between the object and the scanner need to be consider. For this scanner the lens require a working distance of 205mm.

3.1.4 Laser Stripes

As was told before in the LED subchapter, the light source provide light in a special form with some important characteristics. And the projection lens makes the light as a line that is projected on the object. This light is reflected and treated by the collecting lens, so that the CCD camera can capture the laser stripe with the objects shape.

In this Nokra scanner the laser line is formed by points. The total number of points on a line is variable and susceptible to changes through software control. This parameter is directly proportional to the resolution of the image acquired by the camera. The more points, the better the image is and the greater the precision of the measure is.

Every data stripe have two important information from the points. The lateral data, which corresponds to Y coordinate. And the distance data, that represents the Z coordinate from all the acquired points, into the laser coordinate system.

For this model of Nokra laser scanner, the line measuring range is around 60 mm x 50 mm for lateral and distance data, respectively.

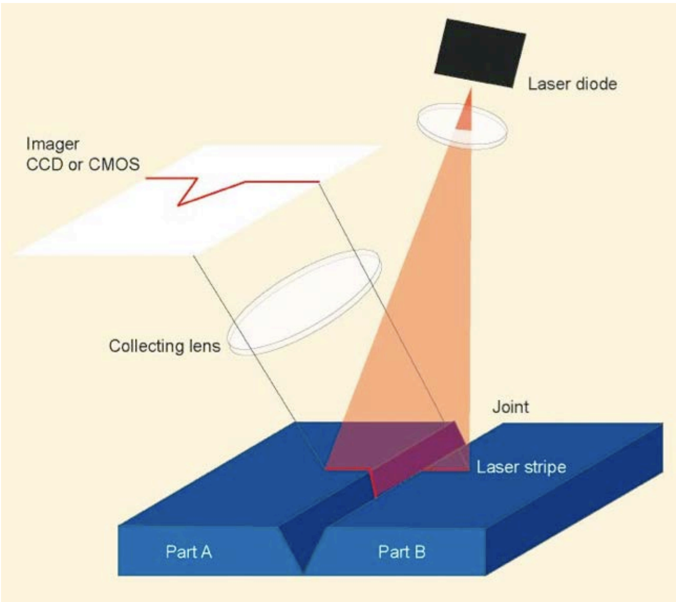


Figure 26 - The laser scanning line.

3.2 Machine Tool

The machine tool used during the project is also made in Germany by a company named Hermle AG. The machine model utilized was C 800 U, which contains five motion axes and a Sinumerik numeric control provided by Siemens.

The points of discussion of the next subchapters will be the geometry, kinematic model of the machine, one of the most important inputs for the integration, and also the counter card that has been installed.

Figure 27 – Hermle C 800U.

3.2.1 Characteristics and Geometry.

The machine model C 800U, contains five motion axes as presented in the Figure 28. The Hermle can be described as two distinct systems. The first one is the table system, place where the part is machined. The second is the tool system, where the tool is held by the machine arm.

The machine is capable to move the his arm, the tool system, around the 3 main axes (X,Y,Z). All the motion limits for each axes and the techinical drawings of the machine are in the appendix A.

The table system can be rotaded or tilted. In the tilting case, which is actually the enforcement of a rotation around the X axis from the table coordinate system. This axis will be called A, for now on. When the table is rotaded, the movement is realized around the Z axis, also from the table system. This axis will be called C.

Figure 28 - CNC motion axis.

3.2.2 Rotary Encoders.

A rotary encoder, also called a shaft encoder, is an electro-mechanical device that converts the angular position or motion of a shaft or axle to an analog or digital code.

To solve positioning problems in automation, it is often necessary to measure lengths and angles as exactly as possible. In general there are two different measuring systems: incremental measuring system and absolute measuring system.

The incremental encoder principle is to scan a line pattern on a glass or plastic disc. The states of the line pattern transparent or not transparent are converted into electronic pulses by an opto-electronic unit (e.g. transparent = 5V, not transparent = 0V).

The analysis of the signals is performed in an evaluation unit by counting up or down with each pulse. The current count is stored in digital form and is instantly available for evaluation.

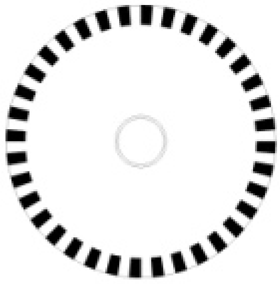


Figure 29 - Incremental encoder disk. [13]

However, this method has some serious disadvantages. After a loss of the supply voltage it is often necessary to return to a reference point, which can cause complications. For these reasons, applications with a high emphasis on precision or applications where it is complicated or not possible to return to the reference point often use the absolute measuring system.

In the absolute encoder every position of the measurement range/angle is identified by a definite code on a glass or plastic disc. This code is represented on the disc in the form of light and dark regions within different tracks. This combination relates to an absolute numerical value. Thus, the position value is always directly available, counters are not necessary. In addition, it is not possible to get continuously invalid values caused by interferences or loss of the supply voltage. Movements which are done while the system is turned off are immediately measured after the system is powered up.

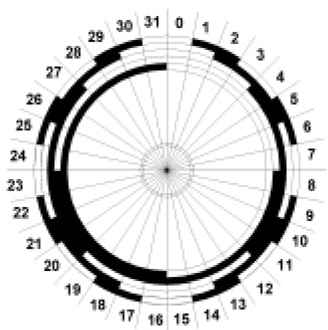


Figure 30 - Absolute encoder disk. [13]

In modern measuring devices with code measuring procedures, a binary code or Gray code are often used. In the Table 4 the different codes are presented.

Decimal	Binary code	Gray code
0	0000	0000
1	0001	0001
2	0010	0011
3	0011	0010
4	0100	0110
5	0101	0111

Table 4 – Grey and binary code.

The gray code has the advantage of being a one-step code, where only one signal changes between measurement steps. Through plausibility queries, the probability of an incorrect position value can be clearly reduced using this code.

The mechanisms to read the both types of disk (incremental or absolute) can be mechanical or optical. In this document is explained the most used mechanism for the CNC machines, which is the optical mechanism.

The optical mechanism for reading this codes consists of a light source, a code disc pivoted in a precision ball bearing and an opto-electronic scanning device. A LED is used as a light source which shines through the code disc and onto the screen behind. The tracks on the code disk are evaluated by an opto-array behind the reticle. With every position another combination of slashes in the reticle is covered by the dark spots on the code disk and the light beam on the photo transistor is interrupted. That way the code on the disc is transformed into electronic signals. Fluctuations in the intensity of the light source are measured by an additional photo transistor and another electronic circuit compensates for these. After the electronic signals are amplified and converted they are then available for evaluation.

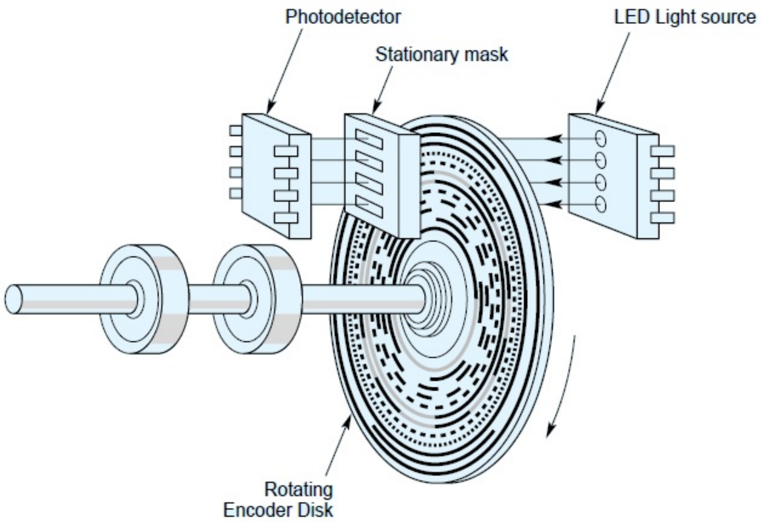


Figure 31 - Encoder optical system.[15]

3.2.3 CNC Magazine.

In the most recent CNC machines the manufacturers tried to make the machine more flexible in other to make the a milling center, a device capable to drill, mill, cut and machine the workpiece.

Looking for a flexible center of work, the insertion of a special place where all kind of tools can be stored became necessary. Based on this reason the magazine has been applied into the new CNC machines. With this new warehouse, the CNC machine now are able to works on a wide range of functions.

The magazine from Hermle C 800 U is capable of storing 29 different tools. The dimensions of the tools are not fixed. One storage cell have their own limit dimensions, in this machine the tool dimension needs to be between 0 and 125 mm of diameter.

3.2.4 CNC Machine Kinematic Model

The CNC Machine kinematic model, is one of the most important subjects for the integration of the CNC and the scanner. This model is a representation of the motion axes, looking to the geometric math. The result will show how the machine probe and the table is positioned in the machine workspace.

In the Hermle C 800 U there are two distinct systems that need to be modeled by the kinematics.

The table as was told before is capable to tilt and round, so the model is modeled by using the rotation in the X axis, which represent the A axis of the machine, and the rotation in the Z axis, which represents the C axis.

In this project, the root system have his origin point (0,0,0) in the center of the table and at the level of the A axis. There are two rotations happening in two different points of the coordinate system as is showed the drawings in the appendix A. The first is the A rotation that is happening in the following coordinates (0,85,0). After the C rotation happens in the middle of the table into the following coordinates(0,0,-39).

4 The integration of Laser Scanner and CNC Machine

At the beginning of this chapter is presented the hardware integration, where it's presented the solutions for the physical integration. After, all the mathematical theory of coordinates transformations from the integration are explained. And finishing the integration, the data acquisition and data handling are explained in the software integration.

4.1 Hardware Integration.

Once the both devices were not designed to work together, some hardware integration were necessary. The solution for the insertion of the laser scanner into the CNC machine will be described in the next subchapters.

4.1.1 Laser Scanner Holder.

To hold the tools, the CNC machine have a special arm. The solution for the insertion of the laser scanner is to put him as a tool in this arm. In this way the laser scanner can be moved in the workspace of the machine. As a result, the scanner will be able to move in all directions to scan the object.

To make this junction between the laser and the CNC, a part for holding the laser were designed, and made in one WZL CNC machine. The top side of the part is simple and very similar to the geometry of a tool, so that the part can fit inside the arm junction. On the other extreme of the part, it was designed a bigger circle in order to join the part with the scanner top. The draw of this part is presented in the Figure 32.

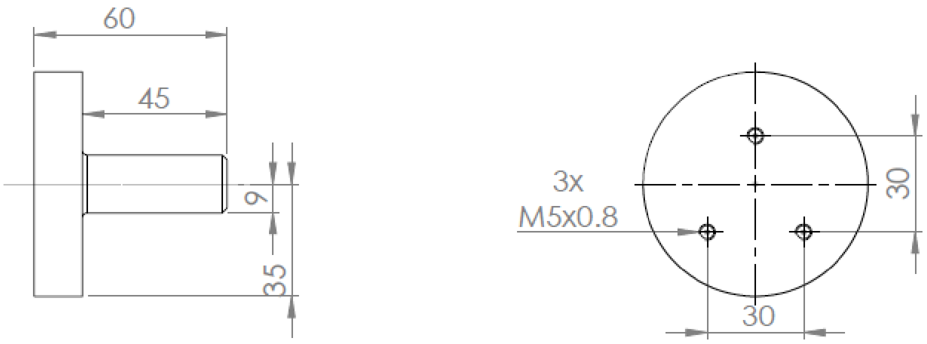


Figure 32 – Laser scanner holder.

The fixation of the part and the laser scanner is performed by three screws as is presented in the Figure 32.

With this part ready, it’s possible to couple the laser scanner into a CNC tool holder, that has fitting dimensions. This CNC tool holder is necessary, once the connection with the arm has a standard, and by using this tool holder will be easier to position in a straight angle. Using a G-code command in the machine the tool holder can go to the zero position, where the scanner is straight as the table.

4.1.2 Laser Scanner insertion into the Magazine.

As was told before the laser scanner should be integrated to the magazine of the machine, this way he will be able to work as a tool from the machine and be called any time the user want.

During the attempt to insert the laser scanner into the magazine two points were crucial to this task not be performed.

- The laser scanner is bigger than the workspace for each tool.
- The Ethernet cable needs to be connected to the scanner.

In order to perform the next steps of the project this insertion of the laser scanner were set as a future work, because a another model of laser scanner needs to be borrowed to make this happen.

4.1.3 Counter Card.

A counter card is a computer device that reads the information from CNC machine rotary encoders by counting the encoder track disk, and present this values into a position value.

For the integration some inputs needs to be acquired. One of these inputs is the actual position of all axes of the CNC machine. Once each of the motion axes, already have encoders to make the position control and seeking for a non-invasive solution, the best option for acquiring the machine positions is to install a counter card into a computer station responsible for the data acquiring. With this solution it will not be necessary to search for position value inside the machine control. In this way the position information is being accessed through the motors encoders and not by the machine control system.

The counter card used in was a Heidenhain IK-220, that can read the encoder position in the interval of 100µs. This counter card board was bought and installed in the computer that is used for the data acquisition for the laser and the machine.

4.2 The Coordinates Transformations

For the integration succeeds some coordinate systems needs to be defined. The tool center point represents the coordinates from the CNC which holds the laser scanner, and is also the data that is read from the counter card.

Since each laser line have a matrix with a variable number of points, the best way of transformation this values to a workpiece coordinate system is by using matrix transformations. All of the matrix representation used in this work will be presented in homogeneous coordinates due to the advantages it offers in the treatment of algebraic points. This way it will be easier to implemented multiplications with matrix-vectors.

The Figure 33 shows all coordinate systems used for positioning the objects into his coordinate system. All the algebraic involved into this transformation can be resolved with one transformation matrix (WT), that multiplied by the laser data points matrix (LL), results the correct values of the object position, as is presented in the equation above.

$$WCS = WT * LL \qquad (5)$$

Looking to discover the WT matrix it will be necessary to discover three other matrix. The first one, represents the kinematic model of Hermle C 800 U in a matricial form. The second orientate the laser scanner data in the right plotting positions. And to finish, a Calibration matrix is responsible for the estimation of not know parameters. So is possible to represent the WT transformations as:

$$WT = KM * T_S * Cal \qquad (6)$$

In next subchapters will show the way to execute this matrix transformation.

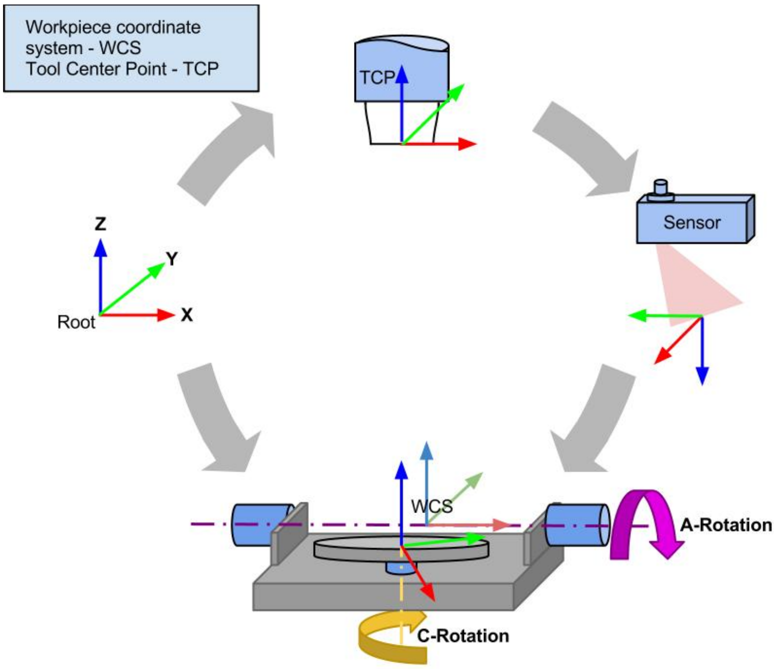


Figure 33 –Transformation coordinates.[12]

4.2.1 Translations Matrix

A translation is movement of every point in constant distance in a specified direction. A translation can also be interpreted as the addition of a constant vector to every point, or as a shifting from the origin of a coordinate system.

Above the translation matrix for each axis is presented.

4.2.1.1 Translation Matrix X

A translation in the X direction, with the X_t distance, have the following representation in a homogeneous matrix.

$$T_x = \begin{bmatrix} 1 & 0 & 0 & X_t \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

4.2.1.2 Translation Matrix Y

A translation in the Y direction, with the Y_t distance, have the following representation in a homogeneous matrix.

$$T_y = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & Y_t \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

4.2.1.3 Translation Matrix Z

A translation in the Z direction, with the Z_t distance, have the following representation in a homogeneous matrix.

$$T_z = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & Z_t \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

4.2.2 Rotations Matrix

The rotations matrix are important for the project, because to describe the motion of the two rotation axes it will be needed a rotation matrix representation.

The two rotation from the CNC machine will be described in the next subtitles.

4.2.2.1 Rotation Matrix A

The A rotation is the rotation around X axis from the table, so the matrix of this rotation can be described as:

$$R_x = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\alpha) & -\sin(\alpha) & 0 \\ 0 & \sin(\alpha) & \cos(\alpha) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where: α = A axis, shifting angle of the Table.

4.2.2.2 Rotation Matrix C

The C rotation is the rotation around Z axis of the table, so a C rotation can be described as:

$$R_z = \begin{bmatrix} \cos(\gamma) & -sin(\gamma) & 0 & 0 \\ \sin(\gamma) & \cos(\gamma) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where: γ = C axis, rounding angle of the Table.

4.2.3 CNC Machine Matrix Model.

The kinematic model of the machine is the model, who represents all motion of the axes together. This model is a critical point for the project development, because without this model it’s impossible to know how the machine is working around of the working field.

4.2.3.1 The TCP translation.

The principal axis of the machine can be easily represented by a translation matrix. The transformation from the Tool Center Point is presented in the matrix.

$$T_{tcp} = T_{Trans\_x} * T_{Trans\_y} * T_{Trans\_z} = \begin{bmatrix} 1 & 0 & 0 & X_t \\ 0 & 1 & 0 & Y_t \\ 0 & 0 & 1 & Z_t \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where: X_t = X axis position of the Tool center point.

Y_t = Y axis position of the Tool center point.

Z_t = Z axis position of the Tool center point.

4.2.3.2 The A axis translation and rotation.

As was told before, in the machine description the rotation center point of the table is not on the origin of the root coordinate sytem. So it’s necessary to do two different movements, first a translation to the center point and after the rotation in X direction.

The presented matrix is the multiplication of the translation in Y and a Rotation around X. That necessary needs to occur in this order, otherwise the result matrix will be wrong.

$$T_A = Trans_y * Rot_A = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & cos(\alpha) & -sin(\alpha) & 85 \\ 0 & sin(\alpha) & cos(\alpha) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where: α = A axis position of the Table.

The value 85 represents necessary motion in Y to reach the A axis. As is presented in the Machine drawings at the appendix A.

4.2.3.3 The C axis translation and rotation.

To reach the table and the object coordinate system, it’s also needed a translation and a rotation in the C axis. The following matrix is presented.

$$T_C = Trans_Y * Trans_Z * Rot_C = \begin{bmatrix} \cos(\gamma) & -\sin(\gamma) & 0 & 0 \\ \sin(\gamma) & \cos(\gamma) & 0 & -85 \\ 0 & 0 & 1 & -39 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where: γ = C axis position of the Table.

The values(-85,-39) are respectively the motion in the Y and Z position to reach the object coordinate system. That are also available in the appendix A.

With this transformation the kinematic model of the machine is done. And now is possible to represent the KM matrix as:

$$KM = (T_A * T_C)^{-1} * T_{TCP} \qquad (7)$$

The first part of the equation is inverse because the movement that is being done is clockwise, so the transformations T_A and T_C are into the inverse side.

4.2.4 The Sensor Rotations.

For the acquired data some transformations are also necessary. Once the laser points are referenced in a different coordinate system. To orientate the scanner data into the right workpiece system, as is presented in the Figure 33, two rotations needs to be performed. First one rotation of 90° around Z axis from the sensor system, and after a 180° rotation around X system. For this transformation it’s used the same equations that were presented in the rotations subchapters.

The result matrix are:

$$T_S = Rot_Z * Rot_X = \begin{bmatrix} 0 & -1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

4.2.5 Calibration Matrix.

The calibration matrix, is the matrix responsible to estimate the distance from the tool center point to the CCD camera. As this distance is not known a calibration is necessary.

To make a calibration matrix it's necessary to acquire some data from a flat surface inside the machine. This calibration test needs to perform pure translation in all the translation axes(X,Y,Z), and also pure rotations around the axes(A,C). With this data a mathematical program from Matlab can run and estimate this calibration matrix(Cal).

The way that Matlab program reaches the calibration values will be presented into the 4.3.5 Calibration subchapter.

4.2.6 The complete Transformation.

The hole transformation necessary for the good referencing of the workpiece can be reached by using algebraic manipulation of matrices. The necessary manipulation is performed in the equation above.

$$WCS = (T_A * T_C)^{-1} * T_{TCP} * Cal * T_S * LL \qquad (8)$$

The last matrix needs to be the laser line matrix(LL), because all the others transformation matrix are square and can be easy mathematically manipulated. On the contrary, the LL matrix have variable dimension, what is not possible to be multiplied all the time during the transformation evaluation.

After all of this transformations the output matrix (WCS) have the shape that is showed into the Table 5. That now are points referenced into the workpiece coordinate system.

X	Y	Z
-22,5810816115571	30,0716725898439	-0,164762911887363
⋮	⋮	⋮
-0,292561784421893	0,552066052947254	0,146927499444781
⋮	⋮	⋮
24,5382831978029	-33,2744410949576	0,498915234715160

Table 5 – Object points.

As this project looks for a 3D model, the points are presented into the (X,Y,Z) coordinate system. And the number rows of this array represents the number of acquired points.

4.3 Software Integration

After all the hardware and mathematical work, the logical part of data collecting and data handling is presented. Labview were used for data collecting, and Matlab for the mathematical modeling, part reconstruction and plotting the result.

The Figure 34 shows the software functions into the integration project, and also presents the data flow during the software evaluation.

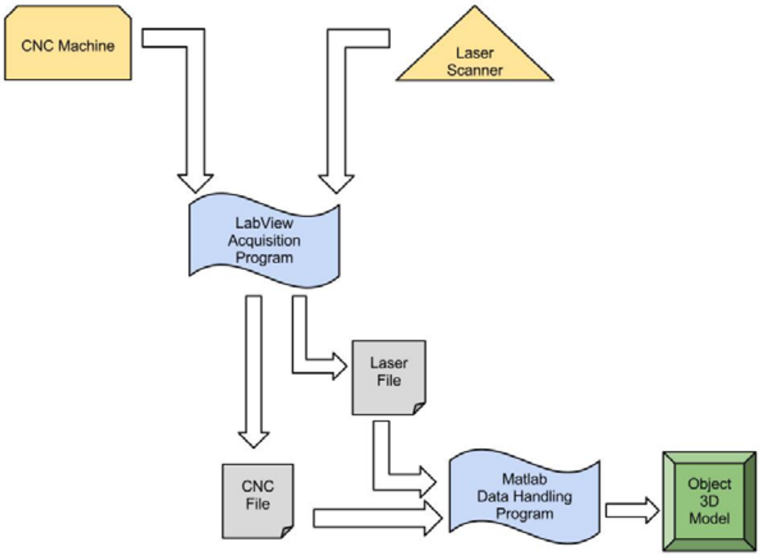


Figure 34 – Software functions.

The CNC Machine information are acquired via counter card by the Labview program and saved into a file. The same happens with the sensor data, which are acquired via CCD camera. This files are the input for the Matlab program, that implements all of the transformations and plot the values into a 3D model.

4.3.1 Labview

Labview is a system design platform and development environment for a visual programming language from National Instruments. In other words, Labview is a system design software, that provides to engineers and scientists the tools needed to create and deploy measurement and control systems through unprecedented hardware integration. The main areas where this software is used are: Data Acquisition, Instrument Control, Test Automation, Analysis and Signal Processing, Industrial Control, Embedded Design.

In this integration project, Labview software is used to acquire data from both devices. Labview was chosen because the counter card and the laser scanner camera were both friendly within. The two devices had some special library in this software what became the integration and the programming a simple task.

4.3.1.1 Labview SubVIs

Labview programs are called virtual instruments (VIs). After a VI is finished, is possible to use it in another VI, in other words a program can be used, as a function, inside a another program. A VI called from the block diagram of another VI is called a subVI. This makes easier to reuse a VI as subVI in other program, and it also makes the diagram cleaner, in the same way that it makes the program easier to understand.

Some manufacturers of acquisition products make a libraries of subVIs for programing development. In this project some of the utilized subVIs were extracted from the Heidenhein counter card library. Also some of the laser scanner subVIs were taken from the Nokra library that was written in C#, and can easy be called by a labview block.

4.3.2 Data Acquisitions

In order to acquire data the Labview program were developed to get simultaneously, the position from the 5 axis of the CNC machine and all the points of the laser line reflected by the scanned object.

4.3.2.1 CNC Machine data

The Machine data format is presented in the Table 6.

Timestamp[ms]	Axis_X[mm]	Axis_Y[mm]	Axis_Z[mm]	Axis_A[°]	Axis_B[°]	Axis_C[°]
0.000	0.000	0.000	0.000	0.000	0.000	0.000
100.000	-20.827	52.993	-43.992	-49.998	0.000	7.499

Table 6 – CNC data form.

Since this machine model don't have rotation around the Y coordinate from the machine all the value in the column of Axis_B coordinate will always remain in zero. This zero value is important because when the data analysis is made, this zero needs to pass through the transformation matrix as the orders values.

The timestamp is the control to know the time interval between the data. Is also used as a control to see if there is any data missing, or even to see if the data from the scanner and the machine are matching in the same time, to see if they are synchronized.

4.3.2.2 Laser Line data

The laser line data are very different from the CNC data. In scanner data, as is presented in Table 7 every three lines represents one sample. This was done this way because of the captured line have an average of 900 points. That's why, the laser file have a variable number of columns. This number of points is a parameter that can be changed in the laser parameters.

Timestamp(ms)	0.000	-	-	-	-
Lateral data	-33.402	…	0.046	…	33.27400
Distance data	0.230	…	0.021	…	-0.470
Timestamp(ms)	100.000	-	-	-	-
Lateral data	-30.344	…	0.003	…	-11.054
Distance data	-22.303	…	-12.754	…	1.252

Table 7 – Laser data form.

With the pair, lateral data and distance data, is possible to plot this point in the 2D coordinate system. As we are moving one axis of the CNC machine, by using matrix transformations, is possible to create a 3D model of the objects with this points coordinates and the machine coordinates.

4.3.2.3 The Main Program

The Labview developed program have one front panel and one block diagram.

The front panel is the interface from the program, where the user can interact and change parameters and watch the program evaluation (Figure 35).

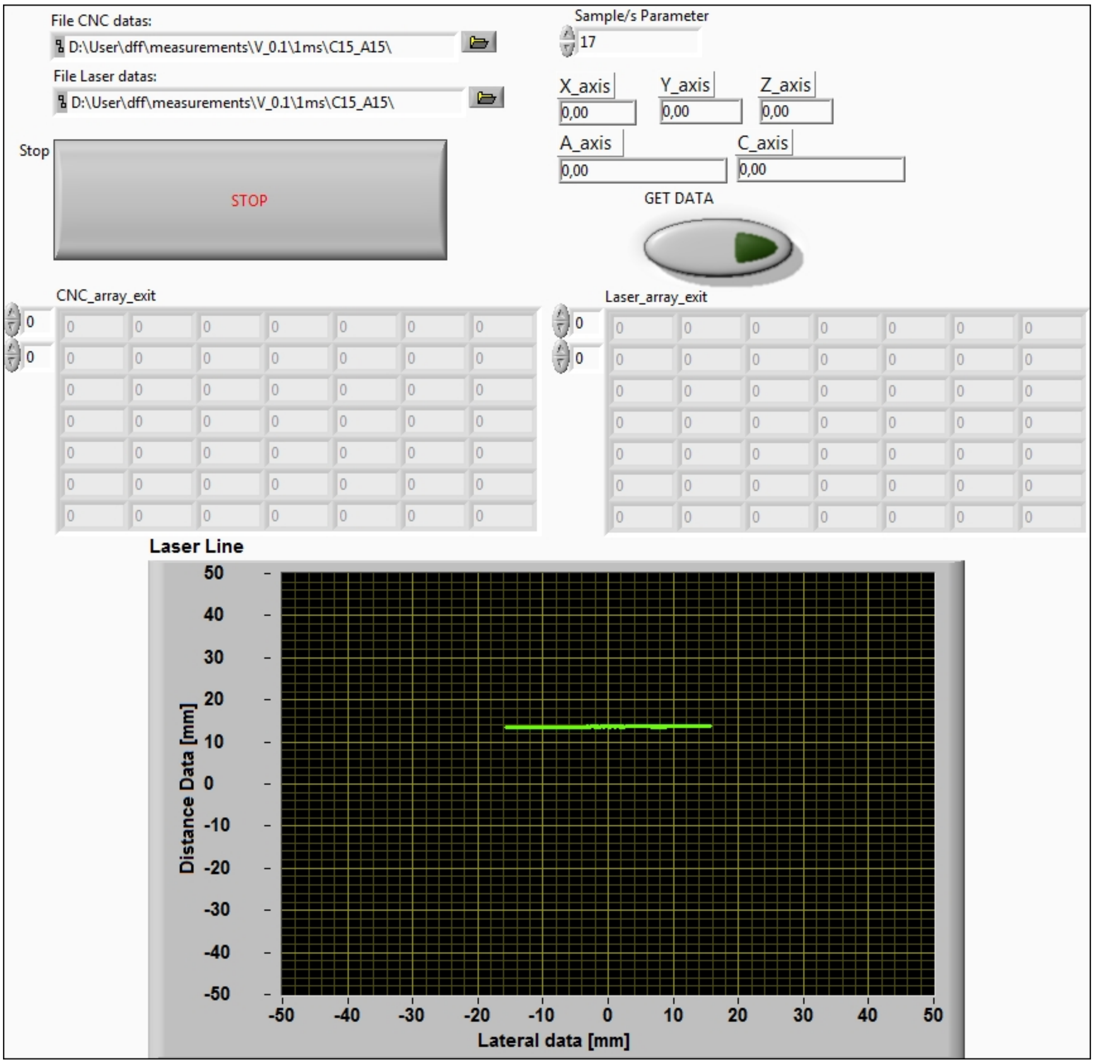


Figure 35 - Labview acquisition interface.

In this interface the user can visualize the actual position of the CNC Machine, and also see all the points from the reflected laser line in a graphic.

To initiate a measurement, the user needs to choose a path, in the File CNC data and the File Laser data input field. This way the array data will be saved with the desired name and the in desired folder. There is one parameter that can be changed by the user in the interface, but it needs to be changed before the user start the program. This parameter is responsible to set the acquisitions sample rate for the counter card.

By pushing the Get Data button the user catch the actual CNC machine position and the actual laser line, then save inside a array for a further processing in the matlab programs. The saved data are available in the front panel, the user can read all the data in the arrays exits table, as a file log.

The block diagram is presented in the Figure 36.

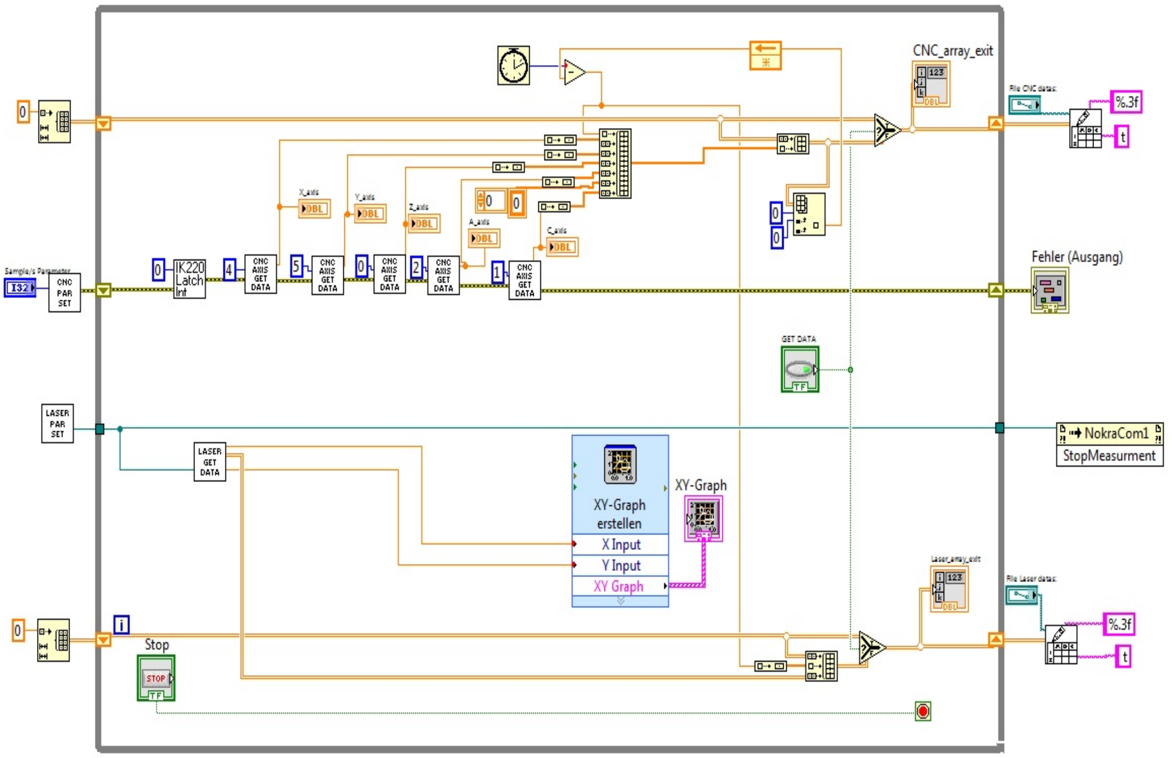


Figure 36 – Labview block diagram acquisition overview.

The program starts with the a round of parameters setting for both devices and also with an array initialization for each device. The Set CNC Par SUB VI performs, all the necessary settings in order that the counter card starts to measure and present the axes position. The Set Laser Par Sub VI makes the parameters setting and starts a Ethernet connection with the laser scanner. These subVIs will be presented later.

Inside the while true structure, is presented a cyclical operation, where image of the CCD camera and all the CNC motors encoders are checked and presented in the user interface. The Get data button is responsible to decide if the actual data will be saved or not into the array exit table. Once the button is performed the data is saved into the array, otherwise the array continues the same as in the last cycle. When the Stop button is clicked, the while loop ends. This way, the actual state of the arrays are saved into the a CSV file, with the chosen name, that were inserted by the user, and also the communication with the laser scanner is closed.

4.3.2.4 The Program SubVIs

The subVIs developed for this main program looked for a better program organization, and an easier visualization of what is being done in each part of the main program.

The developed subVIs used in the program are:

- CNC PAR SET
- SET AXIS
- LASER PAR SET
- LASER GET DATA
- CNC AXIS GET DATA

4.3.2.4.1 CNC PAR SET

In CNC PAR SET the counter card is initialized and parameters, as the sample rate are set. The IK220 Initial subVI loads the firmware into the IK 220 and starts it. In the IK 220 RESET RAM the subVI all the write and read pointers of the RAM buffer is set to 0, in order to initiate a measurement without any other data inside the counter. Inside SET AXIS subVI all the axes parameters, that are being used in the project, are set. As in this project five axis are read, this subVI also have five SET AXIS blocks.

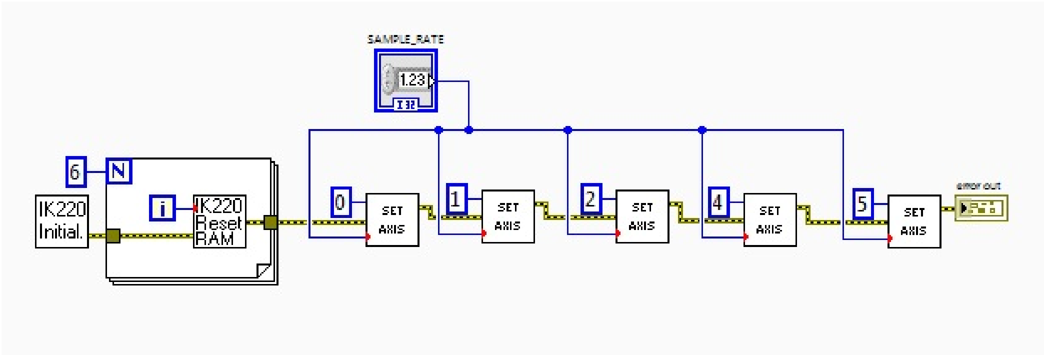


Figure 37 – Counter card parameter set.

4.3.2.4.2 SET AXIS

In SET AXIS subVI the ID Axis is the number identification of the axis that is being set. Each axis receive the sample rate passed by the user in the main program interface. In Write Par subVI, that is also subVI provided in the counter card library, the parameter of the IK 220 is changed to the input data. The first block is sets utilized type of encoder. The second sets the sample parameter, in the desired rate. The third enable the internal clock latch. The last subVI called IK220 MODE RAM sets the latched values that are can or not be transferred. This needs to be set because the values of the measurements are stored in an internal buffer and the values that are read needs to be defined. This value are saved and then, can be read out with IK220GetRam.

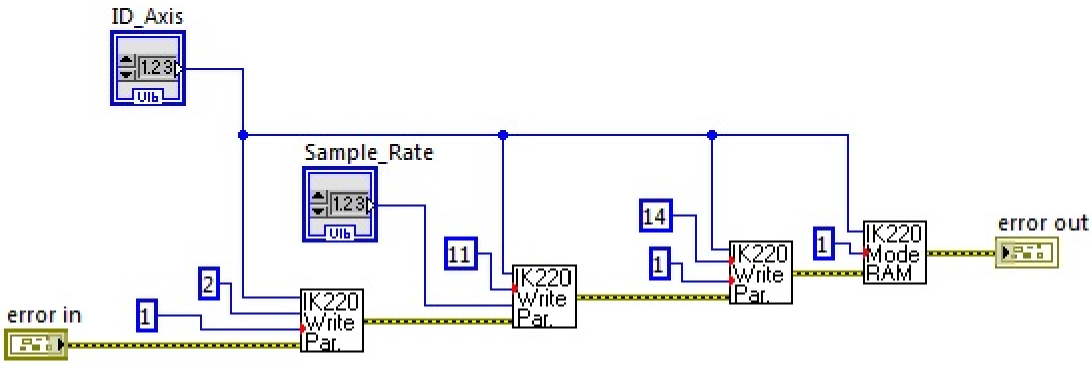


Figure 38 – Axis set parameter.

4.3.2.4.3 CNC AXIS GET DATA

The CNC AXIS GET DATA is the one responsible for catch the data from the memory, make a simple transformation of the read value, and then pass to the front panel axis actual position field.

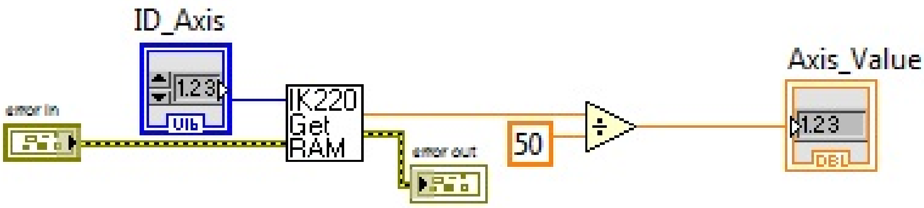


Figure 39 – Acquiring data from counter card.

4.3.2.4.4 LASER SET PAR

LASER SET PAR is responsible initiate the Ethernet communication with the laser scanner computer. After, this measurement can be performed inside the main program. The blocks inside this subVI were developed in C# by the laser scanner manufactucer. All the C# methods can be separately be implemented in Labview as function blocks, as is presented in the Figure 40**.**

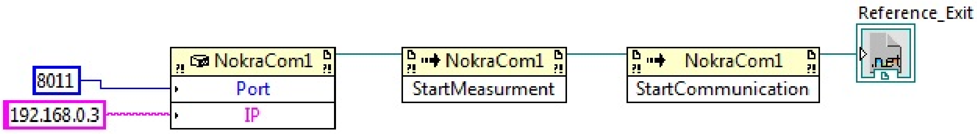


Figure 40 – Laser scanner communication initialization.

4.3.2.4.5 LASER GET

The LASER GET uses also some C# methods codes as diagram blocks in order to read lateral and distance data from the sensor. The both information are putted tougher in a array, and sent to the main interface. This points information are sent to the main front graph diagram to show the actual shape of the laser lines.

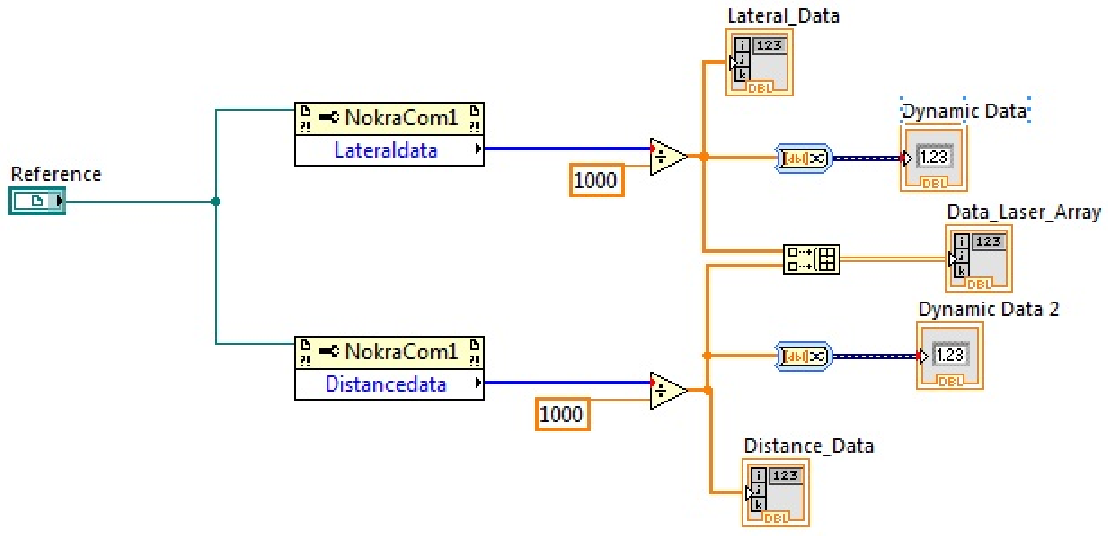


Figure 41 – Laser scanner data acquirement.

4.3.3 Matlab

Matlab is a high-level technical computing language and interactive environment for algorithm development, data visualization, data analysis, and numerical computation. Developed by MathWorks, MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, Java, and Fortran.

Considering that, Matlab perfectly fit to this project application. This software will be used to manipulate the acquired data, manage the mathematical transformation in all the translation and rotation matrix, and also plotting the graphical information of the scanned objects.

4.3.4 Data Handling and Plotting.

Some mathematical manipulation were necessary because of the different coordinate systems. That’s why Matlab programs were developed to handle all of that mathematical transformation of the laser and CNC data.

As was told before in the Labview program the data are collected and saved into the different files. One file from the CNC positions and a another for the sensor data. This two programs are input for all the Matlab programs developed to treat, handle and plot the object in a 3D graphic.

All the data transformations implemented in the Matlab program were presented in the subchapter 4.2 .

The data flow can be described by the Figure 42.

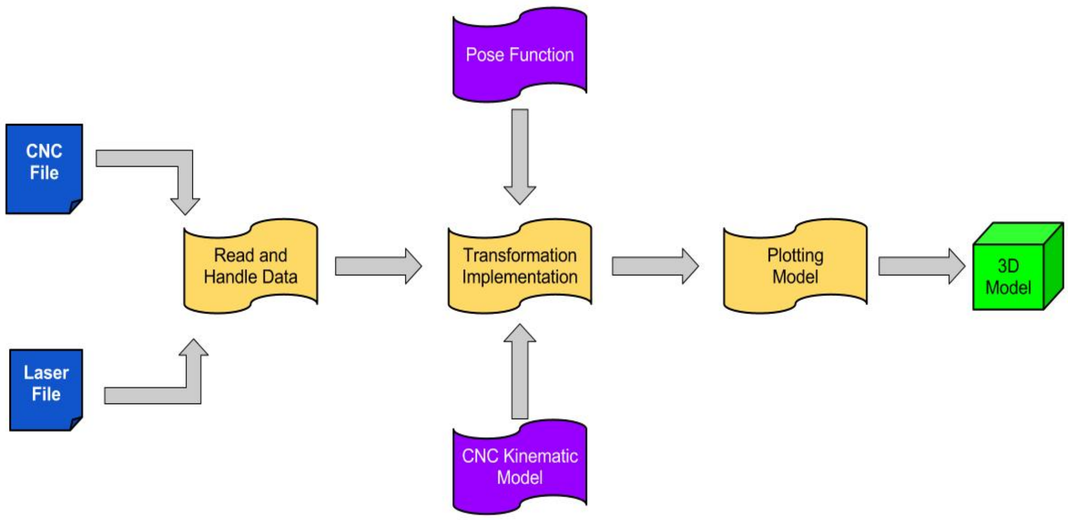


Figure 42 – Matlab data handling and plotting.

CNC file and Laser file are the input for all the process of data handling. This information are accessed and handled to make the laser lines and the CNC position as a homogeneous matrix. After that, the matrix transformations implantation happens, thanks to the CNC Kinematic Model function and also the Pose function. Where the Kinematic Model is the program that translate all the Rotations and Translation necessary to build the KM Matrix as was explained in 4.2.3 subchapter. And the Pose function is the one responsible for manage the translations and rotations according to the Row Pitch and Yaw definition. With this two functions, all of the transformations explained into the 4.2 subchapter are performed. Then inside of the resulting matrix, we have the points, which can be plotted in the same shape, dimension and coordinate system of the scanned object.

4.3.5 The Hand Eye Calibration

The calibration program is the one responsible for find a estimation for the not know values of the transformation between the tool center point and the Sensor Camera.

With this values is possible to find a calibration matrix, which will complete all the necessary transformations to make a 3D model.

To perform this program a measurement of a flat surface is required. In this measurement it’s necessary to have pure translations, and pure rotations in all the machine axes. This measurement is necessary because to find the unknown values of the calibration, it will be used a minimization algorithm. Where the parameter that will be minimized is the distance between the points and the plane.

By the definition that is possible to describe a plane equation with 3 points, the program uses the acquired points, that have already passed thought all the available transformations and also an estimated calibration matrix, to make a plane.

The program runs all points of each line using the distance between the point and the plane equation. All the distance values are stored and after, the mean value of all distances are calculated. So, by changing the values from the estimated calibration matrix, the distance can be minimized, and a plane can be found.

Levenberg-Marquardt algorithm were chosen to minimize this distance values by changing the calibration parameters. This minimization algorithm will be explained into the next subchapter.

The Figure 43 illustrate how the Matlab program deals with this calibration procedure.

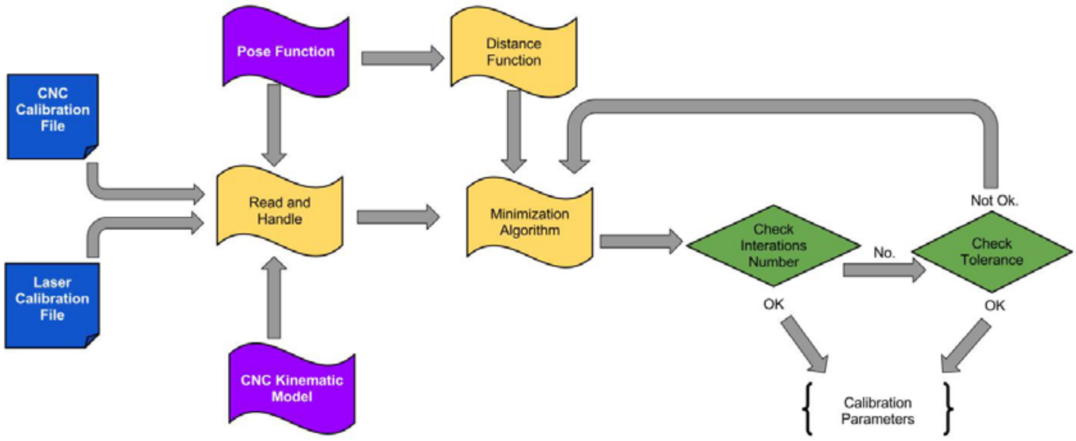


Figure 43 - Matlab calibration.

Data from the calibration test are the input for this program. First, the data are read and handle. Second, all of the transformations and the kinematic of the machine are performed, as was presented into the Data Handling and Plotting chapter. The objective of this program is reach the Calibration Parameters, so as was told before, one function is responsible for bringing the distance value between the laser line and the plane. This function is represented by the Distance function block. That is the input for the Minimization Algorithm, as well as the handled data. The Minimization block runs the Levenberg-Marquardt algorithm, and according on the tolerance given by the user, the program can be interrupted by a good calibration parameter, or can proceed to a next interaction. This Algorithm will run, until the program reaches the desired tolerance value, or until the maximum interaction desired value.

4.3.5.1 Levenberg-Marquardt Algorithm

The Levenberg-Marquardt algorithm (LMA), also known as the damped least-squares (DLS) method, provides a numerical solution to the problem of minimizing a function, generally nonlinear, over a space of parameters of the function. These minimization problems arise especially in least squares curve fitting and nonlinear programming.

The LMA interpolates between the Gauss–Newton algorithm (GNA) and the method of gradient descent. The LMA is more robust than the GNA, which means that in many cases it finds a solution even if it starts very far off the final minimum. For well-behaved functions and reasonable starting parameters, the LMA tends to be a bit slower than the GNA. LMA can also be viewed as Gauss–Newton using a trust region approach.

To explain the Levenberg-Marquardt Algorithm, first we need to consider the non-linear equation:

$$\mathrm{F(Y) = X} \qquad (9)$$

Where X and Y are vectors. Looking to this equation, sometimes it's necessary to estimate a $\widehat{\mathrm{Y}}$ that, leads to a desired $\widehat{\mathrm{X}}$. This problem can be formulated as, by a given $\widehat{\mathrm{X}}$ found a $\widehat{\mathrm{Y}}$ that, minimizes $||\varepsilon||$ from $\widehat{\mathrm{X}} = \mathrm{F}(\widehat{\mathrm{Y}}) + \varepsilon$.

The Newton method, uses the following representation, $F(\widehat{\mathrm{Y}} + \Delta) = \mathrm{F}(\widehat{\mathrm{Y}}) + \mathrm{J}\Delta$ where J is the jacobian Matrix ($\mathrm{J} = \partial \boldsymbol{X}/\partial \boldsymbol{Y}$), and Δ is a small increment. Looking to minimize the $||\varepsilon||$, is the same as minimize:

$$||\varepsilon - \mathrm{J}\Delta|| \qquad (10)$$

The is also equivalent to solve:

$$\mathrm{J^T J}\Delta = \mathrm{J^T}\varepsilon \qquad (11)$$

The solution $\widehat{\mathrm{Y}}_\mathrm{r}$ can be refined using the following equation:

$$\hat{Y}_r = \hat{Y} + \Delta \qquad (12)$$

And can be improved iteratively.

Levenberg made some changes into the Newton Algorithm, in order to accelerate the convergence, by using the following equation instead of the equation (11).

$$\left(\mathrm{J^T J} + \mathbf{I}\lambda\right)\Delta = \mathrm{J^T}\varepsilon \qquad (13)$$

In the begging the λ is equal to 10^{-4}, but during the algorithm evaluation the λ changes according to the results. If the past values leads to a reduction on the residuals, the next λ will be divided by 10. Otherwise, the λ is multiplied by 10.

After the Levenberg alterations, Marquardt noticed some numeric instabilities into the Algorithm, when the λ grows. So looking to that, he proposed that each of the gradient component needs to be weighted according to its curvature, as is presented in the equation (14). So then the algorithm tends to have a great convergence tendency in the direction, where the gradient is smaller.

$$\left(J^T J + \mathrm{diag}(J^T J)\lambda\right)\Delta = J^T \varepsilon \quad (14)$$

As all the other numeric minimization algorithm, the LMA is an interactive procedure. That's why a first guess vector is needed, the algorithm converges only if the initial guess is already somewhat close to the final solution.

Into this project the first guess is six position vector, that corresponds to the six possible movements (Axis) of the camera calibration. So the LMA makes the first interaction, and after by mathematical operations, the algorithm sends new vector values with some corrections. The stopping criteria and the result tolerance is defined by the programmer.

5 Project Achievements.

At the end of this internship document, is possible to list two measurable results. The calibration results and the scanning model results. The tests were did to prove and look for possible mistakes during the implementation.

5.1 Calibration Results.

The calibration results are important to have a good representation model of the scanned object. This result of the calibration will be added as a constant into the plotting program of Matlab, that generates the 3D objects model. This 3D objects tests will be presented in the 5.2 subchapter.

Taking in account the calibration program, the expected result is that the Levenberg Algorithm, will leave all the test lines in a single plane. The parameters that achieve this goal will be the match for the calibration.

That's what the Figure 44 shows, a plane being scanned for the acquisition of calibration values. In the right of the figure is presented the laser lines, without the calibration.

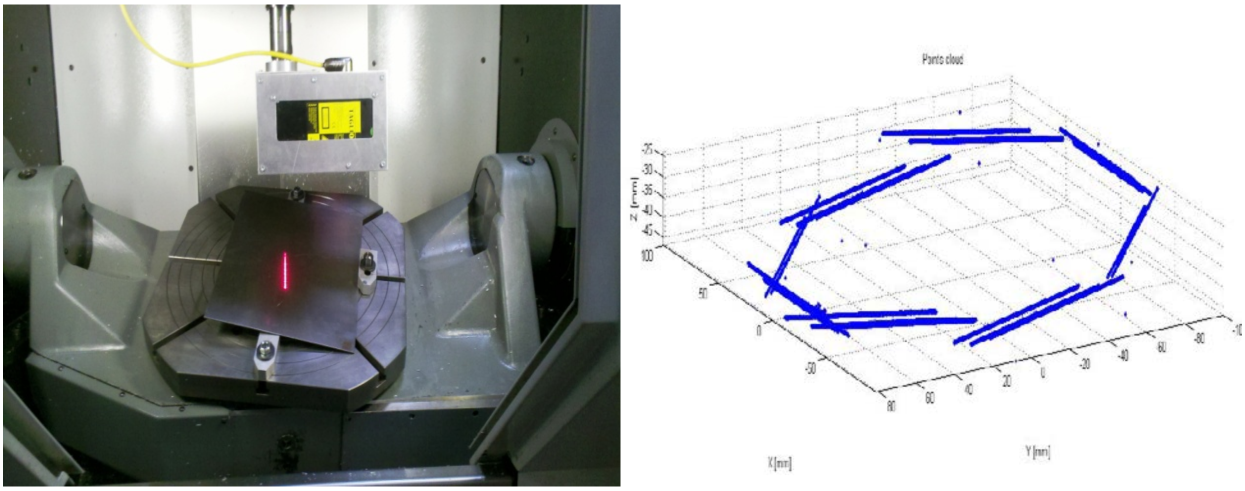


Figure 44 - Calibration procedure and resulting lines without from the plane measurement.

As expected the minimization took all the laser lines to their minimum distance, that’s why is possible to see a plane in the Figure 45. Otherwise the calibration parameters will not be a good approximation. What sometimes corresponds to a local minimum. And will require for a new calibration with different first guess vector.

Figure 45 – Results lines with the calibration parameters.

The calibration values that were given by the calibration program are presented into the Table 8 :

Calibration	X axis	Y axis	Z axis	A axis	B axis	C axis
	0.825377	2.084366	37.035325	0.670237	-11.302116	0.180572

Table 8 - Calibration Values.

5.2 Scanning Part Results.

During the development of the project lots of scanning test were performed, in several ways. The parts were scanned in just one direction, sometimes by moving just the X axis or just the C axis. Other scanning attempts, sought to move two axis, by scanning the part in two parts, to see if the transformations were fitting the data from a different axis position.

5.2.1 The Washer Model

First a non-complex geometry model, were chosen to initiate the testing in objects. The chosen model is a washer (Figure 46). The model dimensions are presented into the Table 9.

External diameter [mm]	Internal diameter [mm]	Height [mm]
41,20	19,75	6,30

Table 9 – Washer dimensions.

Looking for the validation of the whole model of transformation we used three different types of scan to see if all the implementation of the project is working properly. The Table 10 presents the scanning test, that were realized with this model.

Test	Number Scans	Moving axes	Steps
1	1	X	0,50 mm
2	1	C	5,00°
3	2	X,Y	1,00mm/15,00mm

Table 10 – Washer scanning tests.

5.2.1.1 Test One.

Figure 46 shows the part during the scanning test 1. And Figure 47 illustrate the resulting virtual 3D model, of the Washer that were scanned in a single scan as presented in the Table 10.

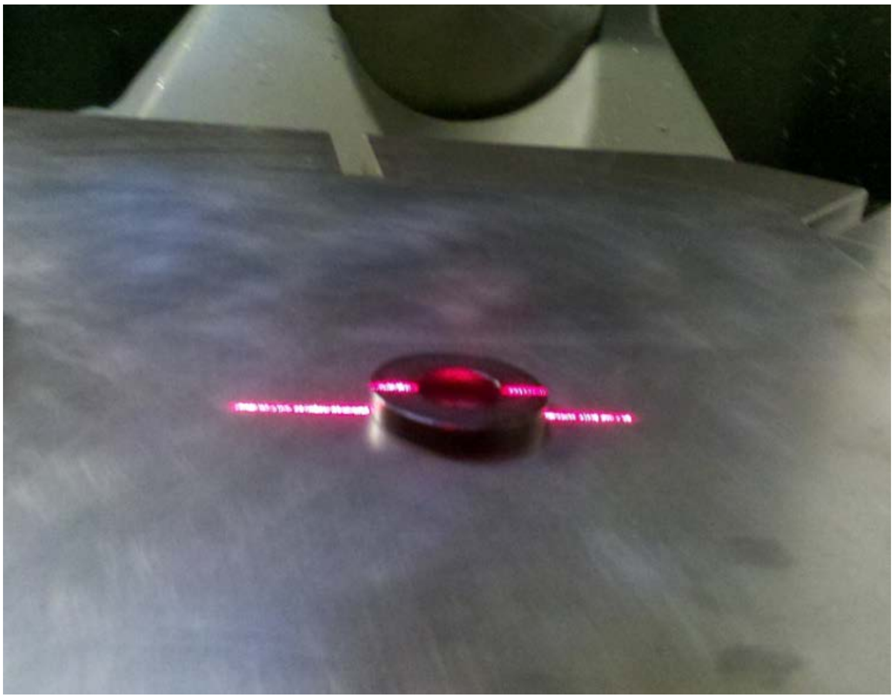


Figure 46 - The real Washer model during the test 1.

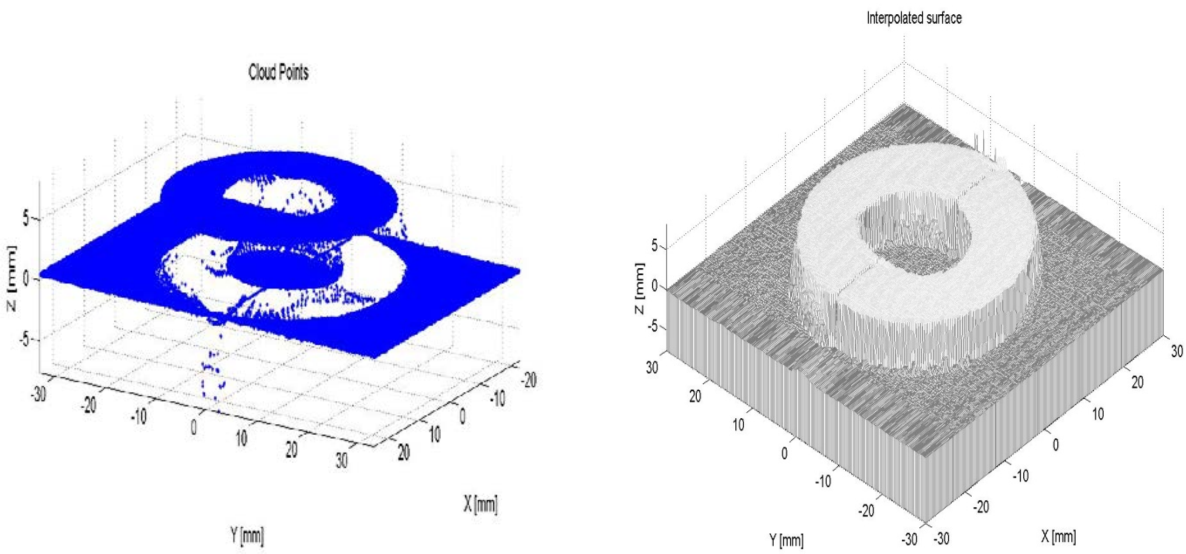


Figure 47 – Lines and 3D model of the Washer, Test 1.

The Cloud Points figure presents all the laser lines scanned, in the shape of a Washer. As is possible to see, lots of points appear as a reflection of the lateral face of the Washer.

The Interpolated surface, shows a 3D view of the Washer model. In this figure is possible to take all the object measurements. The acquired data shows the following results.

External diameter [mm]	Internal diameter [mm]	Height [mm]
40,85	19,92	6,32

Table 11 – Measurement results, test 1.

As we can see in Table 11, there are same errors between the measuring of the real part and virtual model. Table 12 shows the absolute and the relative error in the different part features measurement.

	Absolut error [mm]	Relative error[%]
External diameter	0,45	0,84
Internal diameter	0,17	0,31
Height	0,02	0,15
Errors Mean	0,21	0,43

Table 12 – Measuring errors, test 1.

5.2.1.2 Test Two.

Looking to the other test, Figure 48 presents the resulting virtual 3D model, of the Washer that were scanned in according to the characteristics presented in the Table 9, test 2.

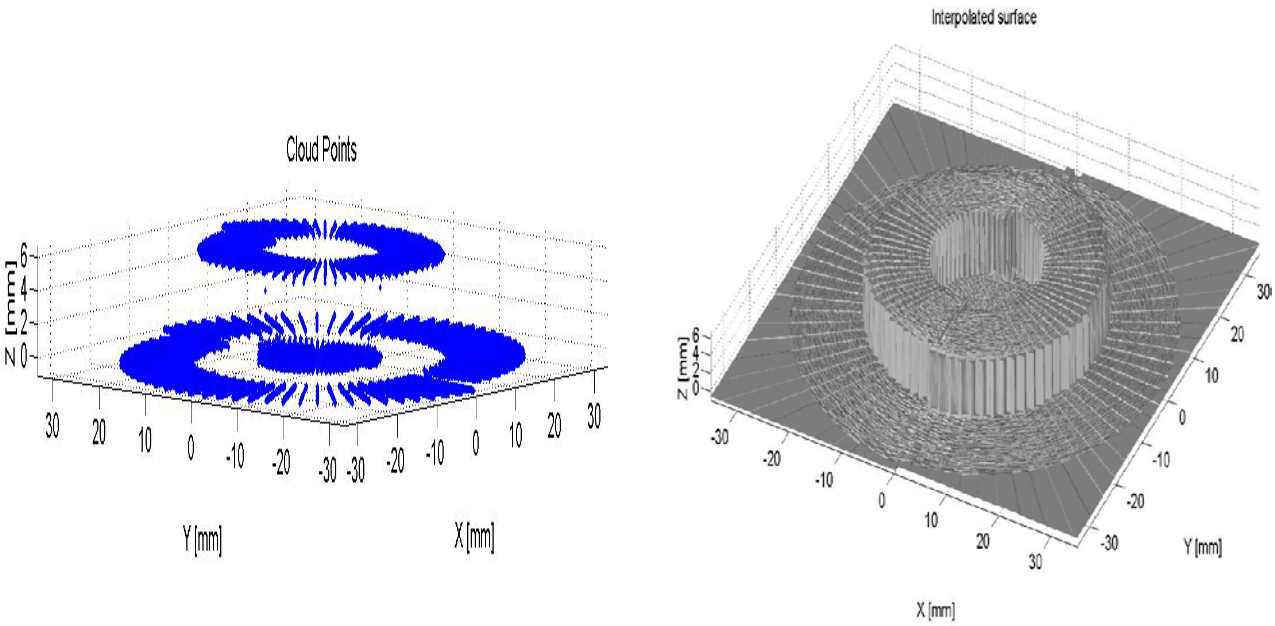


Figure 48 - Lines and 3D model of the Washer, Test 2.

The measurements of the Washer, are presented in Table 13.

External diameter [mm]	**Internal diameter [mm]**	**Height [mm]**
40,12	20,03	6,34

Table 13 - Measurement results, test 2.

Table 14 shows the errors.

	Absolut error [mm]	**Relative error[%]**
External diameter	1,08	2,62
Internal diameter	0,28	1,41
Height	0,04	0,63
Errors Mean	0,47	1,53

Table 14 - Measuring errors, test 2.

As is possible to see into the Cloud Point figure, the lines have a different disposition, because in this case the laser scanner didn't have motion, only the table were the object were centered. The errors looks like in the same proportion as into the test 1.

5.2.1.3 Test Three.

To finish the Washer test, Figure 49 shows the virtual 3D model, of the Washer that were scanned in according to the characteristics presented in the Table 8, test 3.

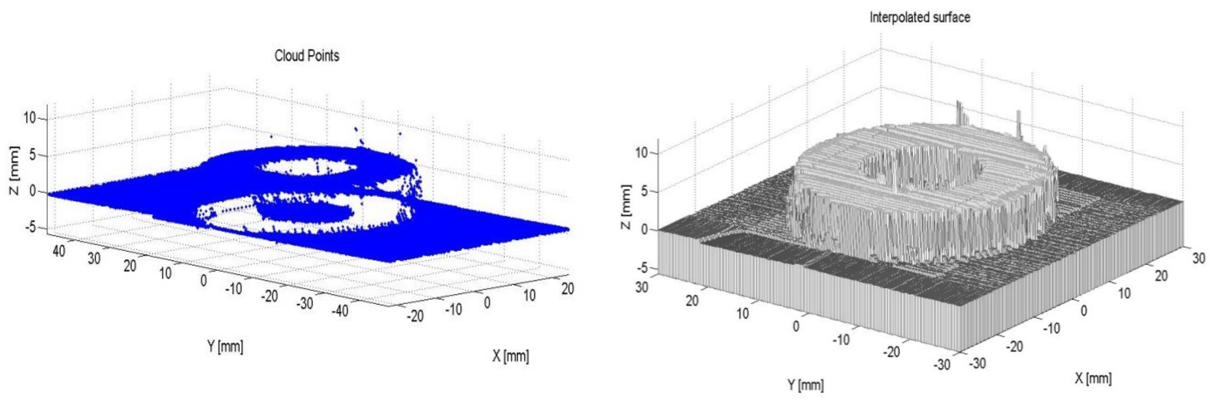


Figure 49 – Lines and 3D model of the Washer, Test 3.

External diameter [mm]	Internal diameter [mm]	Height [mm]
40,60	20,01	6,31

Table 15 - Measurement results, test 3.

The errors associated with this measurement are presented into the Table 16.

	Absolut error [mm]	Relative error[%]
External diameter	0,60	1,46
Internal diameter	0,26	1,32
Height	0,01	0,16
Errors Mean	0,29	0,98

Table 16 - Measuring errors, test 3.

Figure 49 shows the two part scanning where, the first half of the Washer, left side is scanned and after the right half is scanned. In this scanning the X axis and the Y axis were changed. So Figure 49, proves that the fitting data with the calibration matrix and all the transformation are doing their job properly.

After all the three different scanning modes, we can say that the results were almost the same model. Which proved that all the motion tested were working as it's necessary to adjust the acquired data. Looking to the error tables, is possible to say that the measurements are giving some good results and the error, is always turning around 1%. What is a very interesting measurement result, taking in account that others error were included into this final result. As an example of this errors we can cite, the measuring error of the encoders and the scanner camera points.

5.2.2 The Aachener Dom Model.

In order to test limitations of the laser scanner and also the developed transformations, a complex model were chosen to see how robust the developed project are. The chosen model is showed in Figure 50, that is a souvenir miniature of the Aachen Cathedral .

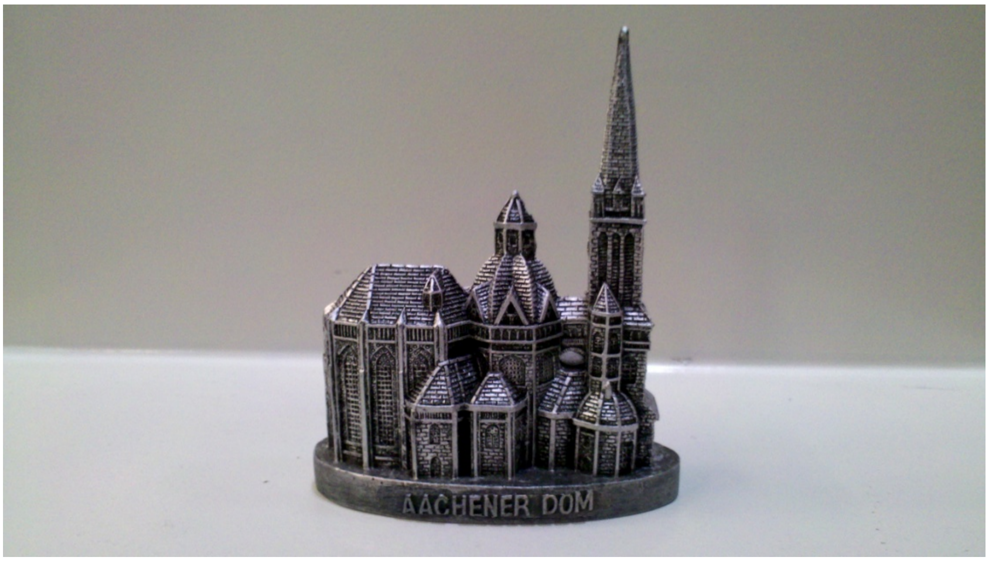


Figure 50 – Aachener Dom real model.

This miniature require for lots of scans and in small steps of 0,5 [mm], considering that this model has a lot of details that need to be acquired.

To scan this object there were necessary to shift the table in the A axis and also adjust the Z axis to make that the reflected lights to be acquired by the camera. In other words to put the scanner into the correct working distance. Then the lateral part of the Cathedral were scanned in two parts the first and the second half, by moving the X axis and the Y axis.

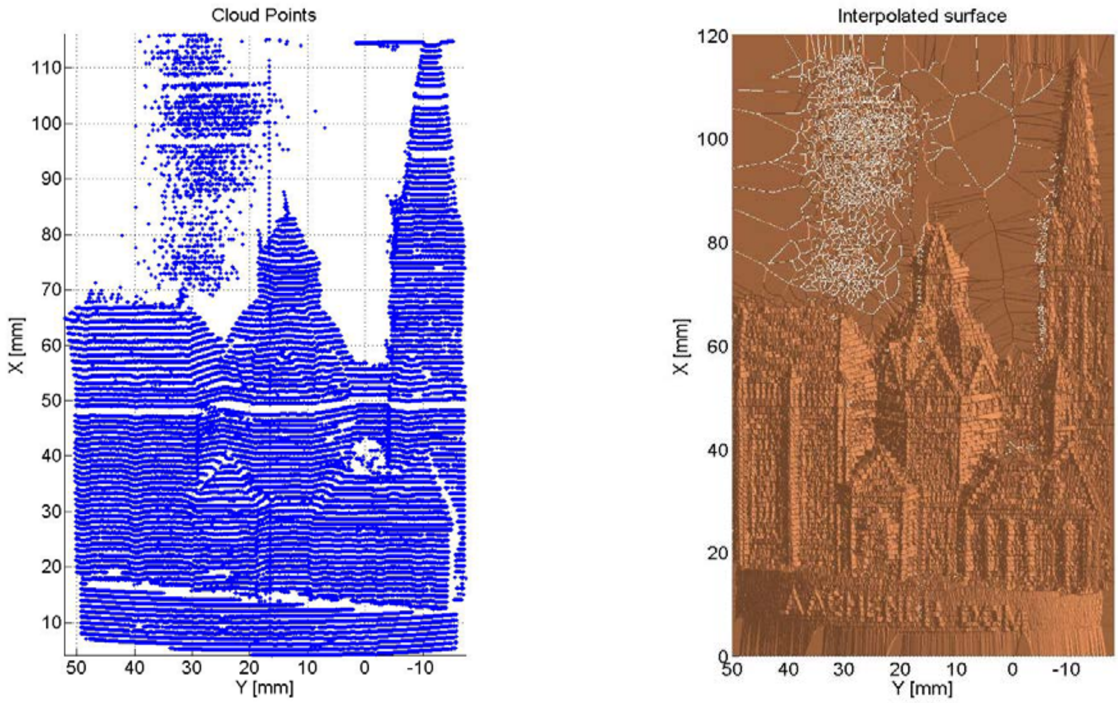


Figure 51 – Aachener Dom virtual model.

The model result is presented in the Figure 51, shows that the laser is working properly, but it is also missing lots of details. This happens because of the two important and well know problems into all the triangulation scanning systems. The first problem is the reflecting problem, where the material can reflect the light in not such a good way. And the second, the shadowing problem.

The shadowing problem can be caused by to different conditions. The first is when the laser beam can't reach all the object surface. And the second case, when the reflected light can't reach the CCD camera.

Is possible to say that the triangulation procedure is spoiled by the shadows when the scanner is placed in a bad perspective position. That's why it leaves some shadows marks into the object model. To solve this problems the measurement needs to be done in different positions, where the light can reach the object, and also be captured by the camera. This can be achieved by turning the table or even tilting the table.

6 Conclusion and Outlook

As a conclusion to this integration project, is possible to say that the insertion of a laser scanner into the CNC machine can happen. By the development of this project, it's presented that the most difficult part of this integration were faced into the mathematical modeling of the kinematic model of the machine and also the transformations that need to be developed.

The hardware integration is done and now the scanner is ready to move and work inside the machine. This project stage was solved with the introduction of a new CNC holder and a junction part.

CNC positions were extracted by a counter card using the encoders position of each axis. Is good to remember that the encoders used is an incremental encoder and each time a measurement needs to be performed the user needs to move the machine into the origin of the system, so that the record positions corresponds to the real positions.

The scanned laser data are being acquired through a Ethernet connection between the laser scanner control computer and the main computer. This data are well shaped and acquired, but it's still but they still are being recorded with a delay compared with the CNC data. That's why the acquisition of the data were implemented in a discrete way to avoid problems with synchronization. So the data are acquired by the user interaction, after he moves the CNC machine he pushes the button to record and save the data from both devices into an respectively array. This is the best option to avoid the non-matching data from CNC and the laser scanner, that was happening in the begging of the implementation of the project.

The mathematical transformations and the kinematic model of the machine, took a long time during the project development. This is the project heart and needs to be carefully implemented, that's why this was the biggest problem during the project.

As a outlook for the future of this project, is possible to list the following steps.

1. Improvement of the model transformations
2. Synchronization of the data acquisition.
3. Incorporation of a laser into the magazine.
4. Real time scanning and modeling.
5. Transforming the data to a CAD model.

The first step is really important for finishing this beginning of the project, and to make the next steps really happen properly.

Synchronization of the data acquisition is a very important step for developing a quicker and more automatic scan. It is clear that the scan trajectory needs to be different according to the object, and forces a CNC programing for each scanned part. But a synchronization brings more agility and saves time.

The incorporation of the laser scanner into the CNC magazine should bring even more agility to the scanning process. During this project this task were not developed due to a dimensional problem, since the laser scanner borrowed was bigger than the limit dimensions and heavier than the weight of the magazine cell.

Another two outlooks, is to realize a real time modeling and also transforming the data to a CAD model. This should bring more quality to the model and also a better supervision to the scanning process. Looking to that, the project might give to the user a better visualization to the actual state of the virtual model.

After all that, the user expectation of measure a part just after the machining procedure, can be achieved by calling a laser scanner as a tool from the CNC machine magazine and starts a scan process. At the end the user will have a CAD model into his data base, that can be measured and inspected.

References:

[1] PFEIFER, T 2002, “Production Metrology”, Oldenbourg.

[2] PFEIFER, T 1992, “Koordinatenmeßtechnik für die Qualitätssicherung“, VDI Verlag.

[3] KUHLHOFF, I 2012, “Sensor data fusion within a industrial inspection machine controlled by a multiagent approach”,Bachelor Thesis, UFSC, Florianópolis.

[4] HARIHARAN, P. 2007. “Basics of Interferometry”, Elsevier Inc.

[5] MELLES GRIOT, 2009, “Introduction to laser Technology”.

[6] NSK , 2012 ,“Ball Screw Tutorial”.

[7] HIWIN Technologies Corp, 2007, “Ballscrews technical information”

[8] GASVIK,K.J 2002, “Optical Metrology”. 3ed, John Wiley & Sons.

[9] BRANDL, M 2002 “Thin Spherical Lenses”, Michigan State University.

[10] The Great Soviet Encyclopedia, 3rd Edition (1970-1979).

[11] Möhrke, G 1992. “Mehrdimensionale Geometrieerfassung mit optoelektronischen Triangulationssensor- Verfahren, Meßunsicherheit, Anwendungsbeispiele.“ Dissertation RWTH Aachen.

[12] BERGHOFF, A 2012,“Integration eines optischen Messsystems in eine 5-Achs-Werkzeugmaschine“ Bachelor Thesis, FH Aachen University of applied sciences.

[13] TW Controls LLC 2012, Absolute Encoders, 07/2012, http://www.patchn.com/index.php?option=com_content&task=view&id=49&Itemid=74#2

[14] The LED Light (China) Co.Ltd 2010, Color Quality of White LEDs, 07/2012 http://www.theledlight.com.cn/304-knowledge-Color-Quality-of-White-LEDs.html

[15] K.N.Toosi University of Technology, Basics - absolute encoders http://saba.kntu.ac.ir/eecd/ecourses/instrumentation/absolute encoders principle of operation.pdf

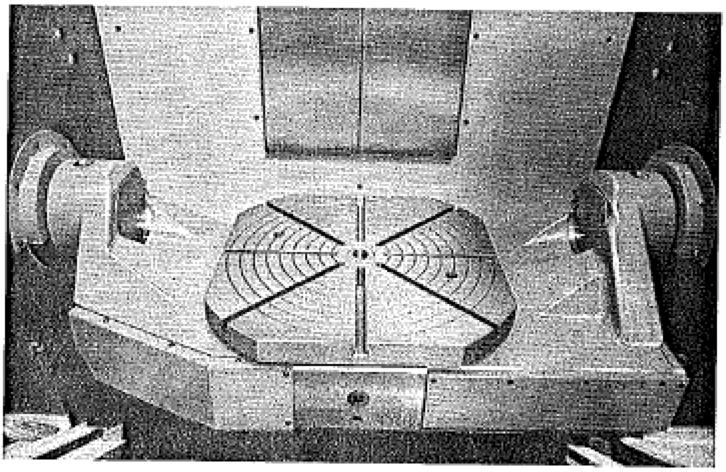
[16] Measurement Equipment Corporation, Scanning Technologies 07/2012, http://www.mecsw.com/reviews/scanners/scantech.html#LED

Appendix A – Hermle U 600 C Technical information

HERMLE

NC-Schwenkrundtisch

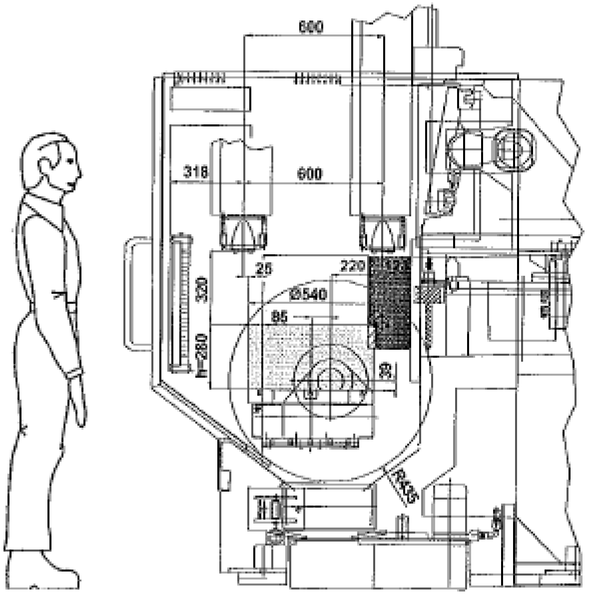
Technische Information

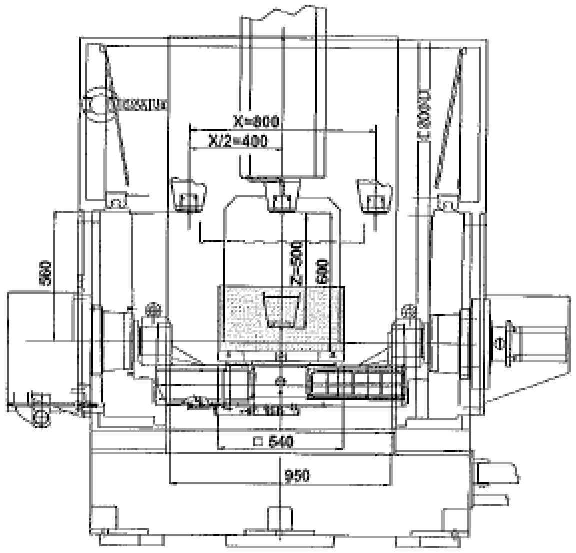


Der nutzbare Arbeitsbereich beträgt in den Achsen:	
X-Achse	800 mm
Y-Achse	600 mm
Z-Achse	500 mm
Aufspannfläche des NC-Schwenkrundtisches:	
Kreis	Ø 630 mm
Quadrat	540 x 540 mm
Belastung des NC-Schwenkrundtisches:	
Tischbelastung	max. 300 kg
Gewicht des NC-Schwenkrundtisches:	
Tischgewicht	325 kg
Schwenkbereiche der NC-Schwenkrundtische (A-Achse):	
A-Achse gesamt	110°
davon nach hinten in A -	- 20°
davon nach vorne in A +	+ 90°
Drehbereich der NC-Schwenkrundtische (C-Achse):	
Drehbereich der Tischplatte	360°

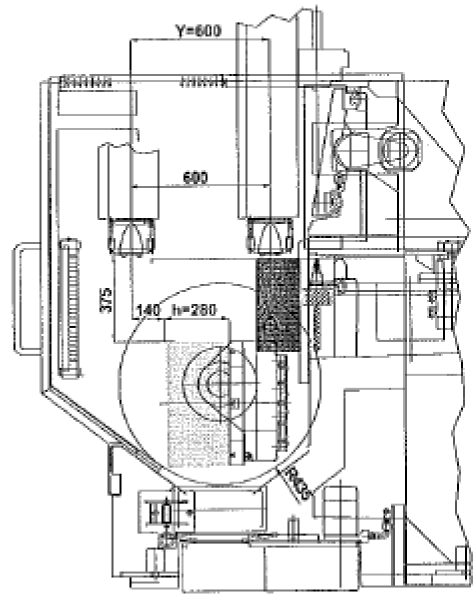
64

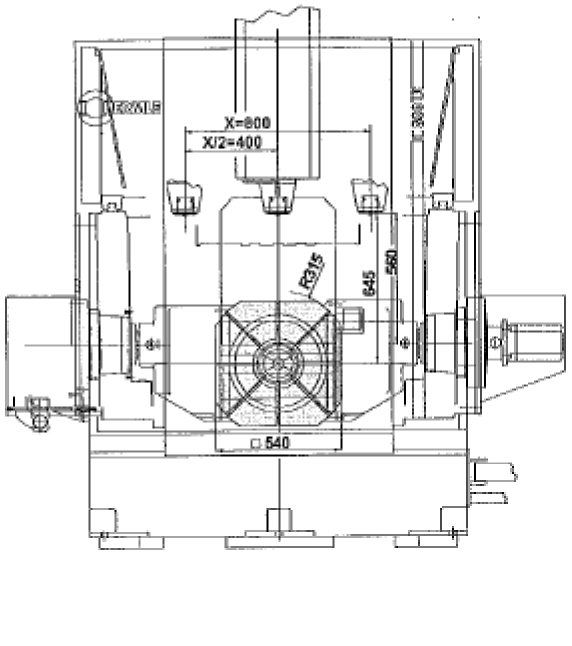
Tisch 0° geschwenkt





Tisch 90° geschwenkt





Appendix B – Matlab programs

```
function []=save_datas(id)
%WZL der RWTH-Aachen%
id
aux=1;
aux1=1;
aux2=1;
count=1;
count1=1;
newcncdata=[];
newlaserdata = [];
laserdata = dlmread(strcat(id,'\laserdata.csv'),'t');
cncdata= dlmread(strcat(id,'\cncdata.csv'),'t');

cnc_folder = mkdir(id,'\cnc');
laser_folder = mkdir(id,'\Sensor');
%% CNC DATA

for i=1:length(cncdata(:,1))
    if(cncdata(i,1) == 0)
        continue
    else
        newcncdata(count,:)=cncdata(i,:);
        count= count+1;
    end
end


timestampscnc = newcncdata(:,1);
cnc_x= newcncdata(:,2);
cnc_y= newcncdata(:,3);
cnc_z= newcncdata(:,4);
cnc_c= newcncdata(:,7);
cnc_a= newcncdata(:,5);



%% LASER DATA

for i=1:1:length(laserdata(:,1));
    if(laserdata(i,1)==0)
        continue
    else
        newlaserdata(count1,:)= laserdata(i,:);
        count1=count1+1;
    end
end

for i=1:3: length(newlaserdata(:,1));
    timestampslaser(aux,:) = newlaserdata(i,1);
    aux=aux+1;
end

%% NEW SHAPE.
```

```
for i=2: 3 : length(newlaserdata(:,1));
    axis_x(:,aux1) = newlaserdata(i,:);
    aux1=aux1+1;
end
z= zeros(length(axis_x(:,1)),1);
o= 1+z;

axis_x= [axis_x];

for i=3: 3 : length(newlaserdata(:,1));
    axis_y(:,aux2) = newlaserdata(i,:);
    aux2=aux2+1;
end
axis_y= [axis_y];

for i=1 : (length (timestampslaser(:,1)))
    laser_point{i} = [ axis_x(:,i)';
                                 z';
                       axis_y(:,i)';
                                o'];
    cnc_axis{i} = [cnc_x(i), cnc_y(i), cnc_z(i), cnc_a(i), 0, cnc_c(i)];
end


%% save the coordenates in the path

cd(strcat(id,'\cnc'));
for i=1:(length (cnc_axis))
        dlmwrite(strcat(num2str(i),'.csv'), (cnc_axis{1,i}), 'delimiter',
'\t','precision', '%.5f','newline', 'pc')
end

cd(strcat(id,'\Sensor'));
for i=1:(length (laser_point))
        dlmwrite(strcat(num2str(i),'.csv'), (laser_point{1,i})',
'delimiter', '\t','precision', '%.5f','newline', 'pc')
end
```

```
function Pose = PoseABC(in)
%%
%%%% Euler Transformation. %%%%
%WZL der RWTH-Aachen%
%
% Transformation by Euler
% Translation: x, y, z
% After Rotation: z(C), y, x(A)
% (C Round, A Tilt)

%% Input variables

Xt = in(1);
Yt = in(2);
Zt = in(3);

angle_alpha = in(4); %Rotation Z
angle_beta  = in(5); %Rotation Y
angle_gamma = in(6); %Rotation X

%% Transformations
RotZ   =  [ cosd(angle_alpha), -sind(angle_alpha),  0, 0;
            sind(angle_alpha),  cosd(angle_alpha),  0, 0;
                            0,                  0,  1, 0;
                            0,                  0,  0, 1 ];
%
RotY   =  [  cosd(angle_beta), 0,    sind(angle_beta), 0;
                            0, 1,                   0, 0;
            -sind(angle_beta), 0,    cosd(angle_beta), 0;
                            0, 0,                   0, 1];
%
RotX   =  [ 1,                 0,                   0, 0;
            0, cosd(angle_gamma),  -sind(angle_gamma), 0;
            0, sind(angle_gamma),   cosd(angle_gamma), 0;
            0,                 0,                   0, 1];
%
Trans =  [ 1, 0, 0, Xt;
           0, 1, 0, Yt;
           0, 0, 1, Zt;
           0, 0, 0, 1];

%% Transformation result

Pose= Trans * (RotZ * RotY * RotX);
```

```
function position = kinematic_hermle(in)
%%
% Hermle U800 C CNC Werkzeugmaschine
% Transformiert die TCP-Postition in das globale Koordinatensystem (Root)
% WZL 2012
%%

%% Variable

%Translations
x_k = in(1);
y_k = in(2);
z_k = in(3);

% Angle in the kinematic function, alpha, gamma negative to the in
% Clockwise rotating machine data in the positive mathematical sense

alpha_k = -in(4); %A-Axis, Tilt
beta_k  =  in(5);
gamma_k = -in(6); %C-Axis, Round


%% A-Axis (Tilt table)

A_Axis = PoseABC([0 85 0 0 0 alpha_k]);


%% WCS (Workpiece coordinate System,on the table. C-Axis)

WCS = PoseABC([0 -85 -39 gamma_k 0 0]);


%% TCP (Tool Center Point)

TCP = PoseABC([x_k y_k z_k 0 0 0]);


%%  Transformation Result

 position = inv(A_Axis * WCS) * TCP;
```

```
function []=save_lines(id)
%%
%Programm to save datas in the Hermle-NoKra-Systems form.
%WZL 2012
%%

Punkte = [];

%% Calibratrion matrix

 Kal = [    0.8254    2.0844   37.0353    0.6702  -11.3021    0.1806];

%% Path definition

cnc_Path    = [id, '\cnc\'];
Laser_Path  = [id, '\Sensor\' ];
mkdir(id,'\Bilder\');


%% Call the files

gefundene_Lichtschnitte = dir([Laser_Path '*.csv']);
n_ima = length(gefundene_Lichtschnitte);

%% Read the data

index=1;
while  index<= n_ima
    %%  Read the laser scanner data
    clear pos data LLSfile;

    LLSfile = fopen([Laser_Path gefundene_Lichtschnitte(index).name]);
    LLSstring = textscan(LLSfile, '%s', 'Delimiter', ' ' );
    fclose(LLSfile);
    data = zeros(length(LLSstring{1}), 4);

    for m = 1:1:length(LLSstring{1})
          clear zahl
          zahl = str2num(LLSstring{1}{m});

          str2num(strrep(LLSstring{1}{m}, ',', '.') );
          data(m, :) = zahl;
    end
     LS{index} = data;

    %%  Read the cnc data
    clear pos data LLSfile;

    cncPosfile = fopen([cnc_Path gefundene_Lichtschnitte(index).name]);
    cncPosstring = textscan(cncPosfile, '%s', 'Delimiter', ' ' );
    fclose(cncPosfile);
    data = zeros(1, 6);
    clear zahl

    zahl = str2num(strrep(cncPosstring{1}{1}, ',', '.') );
    data(1, :) = zahl;
    %CNC-Positon data Transformation
    A{index} = kinematic_hermle(zahl);
```

```
    index = index + 1;
end

%% Ploting the data
%Matrix of resulting points creation
%CNC-Postition[global gesehen](A) * Kalibrierungs-Werte(Kal) *
Lichtschnitt(LS)

for index = 1:1:length(LS)
        Points = [];
        Points = A{index} * PoseABC(Kal)* PoseABC([0 0 0 -90 0 180])*
PoseABC([2.4 15 75 0 0 0])* LS{index}(1:1:end, :)';
        Punkte = [Punkte ;Points(1, :)' Points(2, :)' Points(3, :)'];
end

%Plot
    figure
    h1 = plot3(Punkte(:, 1),Punkte(:, 2),Punkte(:, 3), 'b.');
    title('Points cloud')
    xlabel('X [mm]')
    ylabel('Y [mm]')
    zlabel('Z [mm]')
    hold off
    axis equal;
    grid on;
   %Save the figures
%     saveas(h1, strcat(id, '\Bilder\Rohdaten'), 'png');
%     saveas(h1, strcat(id, '\Bilder\Rohdaten'), 'fig');
```

```
function [] = calibration(id)
%WZL der RWTH-Aachen%
%% Path definition.

cnc_Path = [id '\cnc\'];
Laser_Path  = [id '\Sensor\'];

%% Data call

gefundene_Lichtschnitte = dir([Laser_Path '*.csv']);
n_ima = length(gefundene_Lichtschnitte);

%% The data read

index=1;
while  index<= n_ima
    %%  Reading the laser lines
    clear pos data LLSfile;

    LLSfile = fopen([Laser_Path gefundene_Lichtschnitte(index).name]);
    LLSstring = textscan(LLSfile, '%s', 'Delimiter', ' ' );
    fclose(LLSfile);
    data = zeros(length(LLSstring{1}), 4);

    for m = 1:1:length(LLSstring{1})
          clear zahl
          zahl = str2num(LLSstring{1}{m});
          str2num(strrep(LLSstring{1}{m}, ',', '.') );
          data(m, :) = zahl;

    end
         LS{index} = data;

    %%  Reading Cnc Position
    clear pos data LLSfile;

    cncPosfile = fopen([cnc_Path gefundene_Lichtschnitte(index).name]);
    cncPosstring = textscan(cncPosfile, '%s', 'Delimiter', ' ' );
    fclose(cncPosfile);
    data = zeros(1, 6);
    clear zahl
    zahl = str2num(strrep(cncPosstring{1}{1}, ',', '.') );
    data(1, :) = zahl;
    %CNC- Position data Transformation
    A{index} = kinematic_hermle(zahl);


    index = index + 1;
end

%% The call of Levenberg-Maquardt Algorithm

[x,ssq,cnt] = LMFsolve(@(x)distancefunction(x, A, LS), [0 0 0 0 0 0],
'Display', 0, 'MaxIter', 1500)
```

```
function [mdistance] = distancefunction(x,A,LS)
%%
%%%% Calibraton function. %%%%
%WZL der RWTH-Aachen%
%%
%Definition of the guess for the values of calibration
Tool = PoseABC([x(1) x(2) x(3) x(4) x(5) x(6)]);
All_Points = [];

%% Make Matrix of points
%CNC-Postition[global_vision](A) * Calibration(Tool) *
PoseABC(LaserPosition) * LaserLines(LS)

for index = 1:1:length(LS)
        Points = [];
        Points = A{index} * Tool * PoseABC([0 0 0 -90 0 180]) *
LS{index}(1:1:end, :)';
        All_Points = [All_Points ;Points(1, :)' Points(2, :)' Points(3,
:)'];
end


%% Level and distance from the light intersection estimate for calibration
% Plane equation:  a*x+b*y+c*z + d= 0

X = All_Points\ones(length(All_Points), 1);
a = X(1);
b = X(2);
c = X(3);
d = 1;

% Hessian Form
norm_a = norm([a b c]);
a = X(1)/norm_a;
b = X(2)/norm_a;
c = X(3)/norm_a;
d = 1/norm_a;


%Getting the distance.
distances = [ a b c] * All_Points' - d;

% Standard deviations of the distances, this is minimized in the LMF into
the
% Original plane to come
mdistance = std(distances);
```