OPEN ARCHITECTURE EQUIPMENT FOR A HIGH PRECISION MEASUREMENT AND THREE-DIMENSIONAL MODELING OF THE FREE FORM SURFACES

Cioboata D.[1], Abalaru A.[1], Logofatu C.[1], Traistaru F.[1], Stanciu D.[1], Marin C.[2]

[1] National Institute for Mechatronics and Measurement Techniques, 6-8 Pantelimon Road, 2nd District, 021631, Bucharest, ROMANIA, E-mail: incdmtm@incdmtm.ro)

[2]Valahia University of Târgoviste, Faculty of Materials Engineering, Mechatronics and Rototics, Bd. Unirii, no. 18 - 24, 130082, Targoviste, Romania, E-mail: marin_cor@yahoo.com

Abstract: *With quality control being an important issue in industry, there is a great need for free form surfaces measurements in manufacturing. With manufacturing processes becoming increasingly more flexible, there is also a demand for increasing flexibility of measuring machines. This paper describes the process of developing an automatic measurement system for any free-form surfaces. We present a system for 3D surfaces measurement with three inter-changeable measurement heads which can be easy mounted on its Z axis and allow contact or non-contact measurements. The paper presents also some considerations about error sources and system calibration. This system is developed under the project: „Researches on advanced control techniques based on the analysis of errors and three-dimensional modeling for a high precision measurement of the complex surfaces"funded by National Program Partnerships in Priority Areas.*

Keywords: *free form surface measurement, optical triangulation, laser scanner, coordinate measurement, non contact measurement, three dimensional surface modeling, open architecture*

1. INTRODUCTION

Inspection plays an important role in modern manufacturing processes. Inspection generally involves a time-consuming operation, and therefore, has been creating serious bottlenecks in production lines.
Various industrial applications require highly accurate, fast and safe measurement of free-form objects geometry. With manufacturing processes becoming increasingly more flexible, there is also a demand for increasing flexibility and integration of measuring machines. Various techniques and methods of 3-D part measurement have been introduced and employed in industrial environments over the years. Nevertheless, the problem of precise and fast measurement of complex surfaces is far from being solved for the industrial field.
Currently the most developed systems used in the industry are systems with stylus which can measure the profile in a given section (2D measurement). For 3D measurement of the surfaces are used mostly templates or coordinate measuring machines.
Coordinate measuring machines are nowadays widely used for a large range of such measurement tasks. For regular geometric features, coordinate-measuring machines (CMM) can be used effectively to assess the accuracy and tolerances. For parts with free-form surfaces, the inspection becomes complex.
As an expensive machine, however, the CMM cannot be considered the best choice for free form surfaces measurement. One of the main reasons is that the touch trigger probe, which is accepted as a touch sensor in most CMMs, results in a low efficiency in the measuring a work piece where a large quantity of points must be detected to define and evaluate the profile of the surface. Another problem brings in practice by the touch trigger probe is that an offsetting operation is necessary for obtaining the surface profile from the measurement data.
However, it is sometimes very difficult how to perform an appropriate and correct offsetting calculation for a measured profile in unknown forms, especially, in situations where there is a large number of measured points.
On the other hand, as an efficient inspection method of complicated profiles, automated laser scanning measurement is a potential technique.
In recent years, due to the development of laser technology, the accuracy of laser scanners has been improved significantly so that they can be used in a production environment. They are noncontact-type-measuring devices.
Non contact measurement methods are faster and capable of collecting a large number of data points.
In the last decade various non-contact methods were developed and tested, and the majority of them were materialized in systems of measuring the quality of surfaces, the absolute 3D measurement of the surface profile being yet a challenge in the industrial environments.
In this paper we present a flexible equipment with open architecture for free form surfaces geometry measurement, by contact or non contact measurement (depending on shape characteristics, material and environment conditions).
Non-contact free form surface measurement is widely used in industry, especially in metrological laboratories, but, in order to reduce time and costs while maintaining a good accuracy level there is a growing trend towards the use of measurement systems based on optoelectronic methods for flexible automated 100% inspection of parts in sectors such as the automotive industry.
We intend to develop an equipment which can be used both in manufacturing workshops and in laboratories.
One of the factors that affect the measuring accuracy is the sensor's resolution. A high resolution sensor usually has a short measuring range. But an unknown profile

with large height variation can't usually be measured using a short range sensor.
On the other hand in manufacturing processes sometimes is necessary a very rapid measurement process but not a very high resolution. At the same time the measured surfaces can have different particularities. They can be shiny, transparent or matte, rough or soft, with regular or irregular profile, with grooves or holes.
For this reason we want to create an equipment for high precision and high speed measurement of complex surfaces that integrates:

- stable mechanical elements;
- inter-changeable measurement heads, based on different contact or non-contact measurement principles (figure 1), selectable according to the particularities of the measured surface, the form and sizes of the profile, the measurement precision and the environmental conditions;
- an operating program for data processing, signal filtering, compensation of systematic errors and three dimensional modeling of the measured surface;
- multiple channel data acquisition and processing systems, for capturing analogical and digital signals, with the capacity to acquire and process over a million measuring points;
- friendly interface for industrial operators.

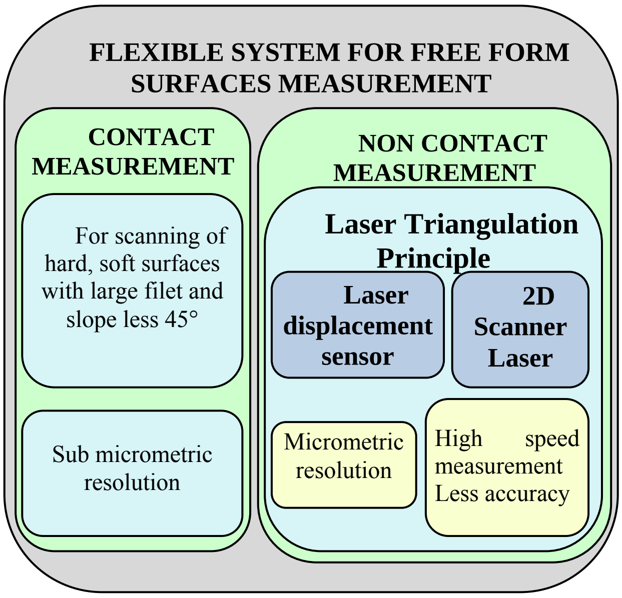


Figure 1. Measurement principle

2. MACHINE DESIGN

The measurement equipment performs the following functions:

- Collecting the data points on the work piece surface;
- Transmission and adaptation of the signal from the transducers;
- Data processing;
- Surface reconstruction;
- Comparison the measured profile with theoretical profile;
- Results presentation under the form of spatial maps and measurement errors.

The main components of this equipment fall in two categories: hardware components and dedicated software. Hardware components include all the physical components that are responsible for the transmission, sensing and control of the equipment motions. The main hardware components are:

- Mechanical system with the three axes, motion transmission components and distance transducers;
- Three interchangeable measurement heads with different measurement probes.
- Control unit (for to control the motion of moving parts);
- PC with peripheral equipment and software to calculate and represent results.

The function of dedicated software is to facilitate the measuring process, surface reconstruction and comparison with theoretical profile.
For to design this equipment we took in account following main attributes: the measuring capability, the accuracy, measuring time, data processing and costs.
One of the most important factors that influence the measuring results is the configuration of equipment. A good accuracy result needs a high precision mechanical structure, capable of positioning the sensorial element in any point of its working volume in an extremely repeatable mode. The mechanical structure of measurement equipment is characterized by two parameters: dimensions and architecture. The first parameter determines the measuring range and can influence the architecture of the equipment and the measuring uncertainty.
We designed the architecture to optimize: dynamics performance (speed and acceleration, metrological characteristics, accessibility to the part to be measured, flexibility (by using of different measuring heads based on different principles), costs. We tried to maximize the rigidity of the structure reducing the relevant mass, in order to obtain the highest possible acceleration (and deceleration), so to improve the dynamic parameters of the measurement equipment.
We opted for the fixed bridge architecture (figure 2) because this construction is versatile and suitable for many measuring applications from simple geometry part to complex geometry parts. Equipped with proper sensors, the fixed bridge architecture can be used for high precision continuous scanning.
In this type of architecture the bridge frame is fixed to the machine base. The machine base is made of grey cast iron and the bridge of steel tube. The joints of the bridge's components are adjustable.

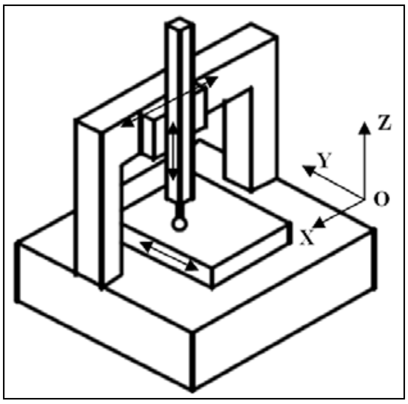


Figure 2. Fixed bridge architecture

The equipment's coordinate system is OXYZ.
The Y-axis movement is realized by the moving table, which translates on the base (figure 3) for positioning the measurement section on transversal direction. The moving table is driven by closed-loop DC motor with shaft-mounted position encoder and precision gearheads providing 0,1 μm minimum incremental motion (encoder resolution 3 nm) and low-friction leadscrew. Precision crossed roller bearings guarantee 2 μm/100 mm straightness of travel.

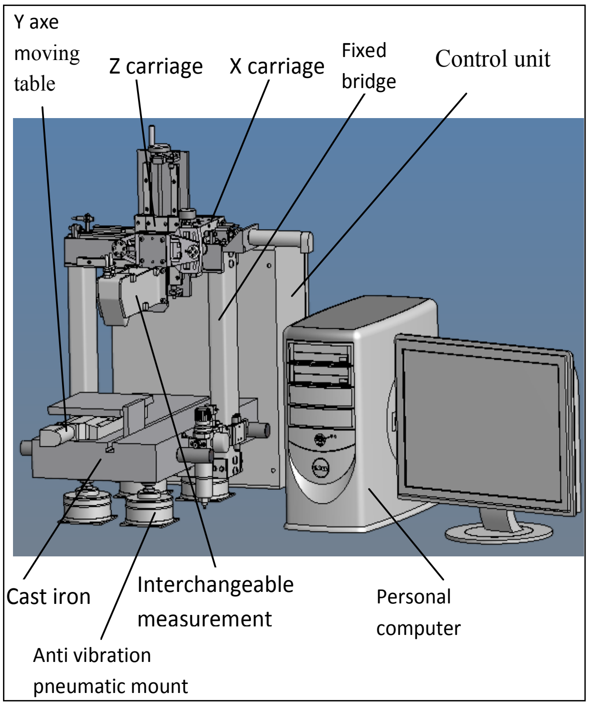


Figure 3. Surface measurement equipment

The longitudinal motorized carriage, mounted on the bridge, moves the scanning head on X direction and controls this movement. The Z - direction carriage is driven manual and it is used for vertical positioning of the scanning heads.
After surface scanning, a uniform mesh of points results from the digitalization. Points belonging to the surface and the contour of significant elements are identified by comparison with theoretical profile and the measurement tasks are performed.

3. THE MEASURING PRINCIPLE

Many different technologies can be used to build a 3D scanning device. The purpose of the 3D scanning systems is to create a point cloud collected on the surface of the measured work piece. These points can then be used to extrapolate the shape of the work piece (a process called reconstruction).
For 3D profile measurement, a single scan on a direction is not enough. Multiple scans, even hundreds, of different paralel sections are required to obtain informations about 3D work piece geometry. These scans have to be brought in a common reference coordinate system and then processed to create a complete model.
There are a variety of technologies for digitally acquiring the shape of a 3D object. Each technology comes with its own limitations, advantages and costs. For example, optical technologies encounter many difficulties with shiny, mirroring or transparent objects.
For to create a flexible equipment, we designed a measuring system on whose Z axis can be fixed inter-changeable measurement heads based on different measurement technologies. These measuring heads can be easily integrated to a processing system by standard communication ports.
We proposed two types of scanning techniques (figure 1):

- **Contact-based technique**

Contact-based techniques can achieve high accuracy rates and are suitable for a wide range of measurement applications. However, these methods offer lower measurement speed because they involve mechanical movement on two axes (X and Y).

- **Non - contact based techniques**

Optical triangulation is one of the oldest and most well known non contact measurement techniques.

We realized two measurement heads based on laser triangulation technique:

1. Point Laser Triangulation Probe

Point Laser Triangulation probes (figure 4) have a number of significant advantages over contact scanning probes hat make them very useful in free form surfaces metrology. Some of these advantages are: zero contact force, large range of measurement, high bandwidth.
Measuring principle is laser triangulation, that means the measurement of distance by calculating the angle. A laser diode projects a visible light spot onto the measurement object. The reflected light is imaged by an optical receiving system onto a position sensitive element. If the light spot changes its position, this change is imaged on the receiving element and evaluated.
We used a sensor with following specifications:
Measuring range: 100mm;
Measurement rate: 20kHz
Start of measuring range: 70mm;
End of measuring range: 170 mm;
Linearity: 30 μm;
Resolution: 1,5 μm.

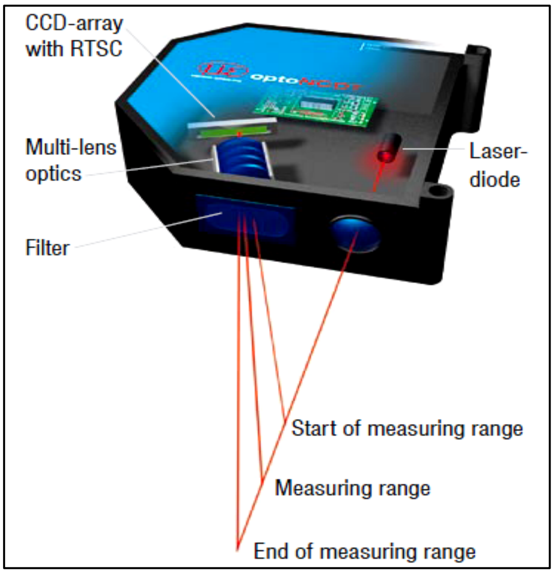


Figure 4. Point laser triangulation probe

This sensor can be replaced with a similar sensor with a better resolution but with less measuring range.
The precision of this type of laser is influenced by the **reflection factor of the target surfaces** [5].
In principle the sensor evaluates the diffuse part of the reflected laser light (fiure 5).

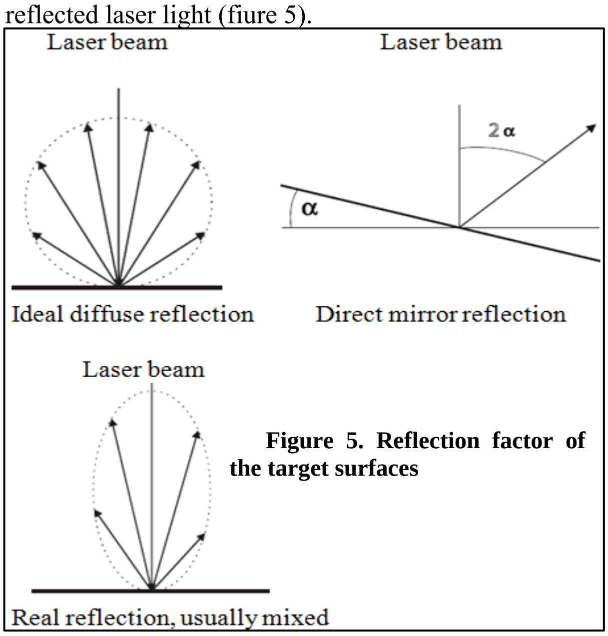


Figure 5. Reflection factor of the target surfaces

A statement concerning a minimum reflectance is difficult to make, because even a small diffuse fraction can be evaluated from highly reflecting surfaces. This is done by determining the intensity of the diffuse reflection from the CCD array signal in real time and subsequent compensation for intensity fluctuations. To use the sensor on transparent or reflective objects, manufacturer pretesting is necessary.
Digital value output conversion of this sensor is calculated with formula:

2. Line range laser sensor

Line range laser sensor collects thousands of points of data per second, making digitizing significantly faster than point non contact measuring technologies without sacrificing accuracy. It is a very rapid profile sensor [4].
This sensor operates according to the principle of optical triangulation (light intersection method) [6]:
-- A laser line is projected onto the target surface via a linear optical system.
-- The diffusely reflected light from the laser line is replicated on a sensor array by a high quality optical system and evaluated in two dimensions.
The laser line triangulation corresponds in principle to the triangulation of a laser point. In addition, during the measurement process, apart from the distance information, (Z-axis), the exact position of each point on the laser line (X-axis) is also acquired and output by the system. The sensors in the probe take measurements over the whole line at the same time instead of measuring just one point of light, as with a point range sensor. This reduces scanning time dramatically.

2D scanner specification:

Measuring range - Z-axis: 250 mm
Start of measuring range (SMR): 100 mm;
End of measuring range (EMR): 350 mm;
Linearity- Z- axis: ±0.1…0.15% of the Z-range;
Working range- X-axis: 100 mm
Linearity- Z- axis: ±0.2% of the X-range;
Max profile frequency: 3.000 profiles/s;
Sampling rate: no less 100 Hz (for the full range).

This sensor can be replaced with other similar sensor with better resolution but with less measuring range.

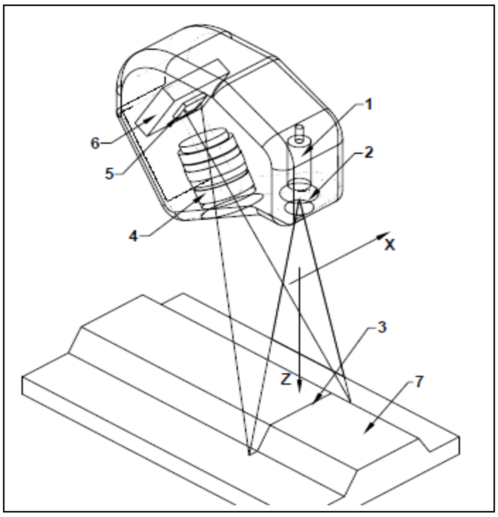


Figure 6. 2D laser scanner

4. ERROR SOURCES

Being a complex machine, with multiple axes and used for complex measuring tasks, with high accuracy specifications, this equipment has many error sources.
In case of measurements using a contact probe, geometric errors of equipment, probing and fixing errors of the probe assembly, probe radius and environment affect the measuring accuracy. In case of measurements using the non contact measuring systems, geometric errors of equipment, calibration errors, fixing errors of

measuring head, optoelectronic measuring system errors and environment affect the measuring accuracy.
Based on the functional components of the equipment, an overview will be given of the most important error sources affecting the accuracy of measurements:

• *Mechanical system*

The main components of the equipment structure are: the table for supporting the measurement objects, the portal, the guide ways, and the carriages with the bearings. These components are causing errors due to inaccuracies related to manufacturing, adjustment and component properties such as stiffness and thermal expansion. The nature of these errors can be static or quasi-static, as well as dynamic.

• *Drive systems*

The axes are equipped with drives and transmissions units. Errors that can be related to the drive system and may affect the measuring accuracy are: mechanical load on the carriage causing unwanted carriage motion, and introduction of vibrations to the mechanical structure. Positioning errors are in general not important, since the coordinates of measurement points are derived from the measured positions (by the scales) and not by the commanded positions.

• *Measurement systems*

For contact measurement system and non contact measurement with point laser triangulation probe the actual coordinates of the measuring points are derived from the values indicated by the linear scales of the X and Y directions. For non contact measurement with line laser triangulation probe the actual coordinates of the measuring points depends only on the values indicated by the linear scales of the Y direction.
The main errors introduced by the scales are inaccuracy of the scale pitch, misalignment and adjustment of the reading device, interpolation errors, and digitisation errors.
Several error sources can be distinguished with the probe systems.

For contact measurement probe the main sources of errors are: hysteresis in the stylus support, radius of stylus compensation and errors in the measuring system.
Tactile digitization of workpiece surfaces is often preferred to optical methods due its higher accuracy. But in this case a problem is that the measuring equipment provide the coordinates of the probes center and not those of the real contact points.
The influence of stylus tip radius must be corrected. This correction is an offset of normal vector in each measured points, equal to the effective stylus tip radius R which is added to the measured points to estimate the actual contact or measured points on the profile (fig. 7).
We use B splines for to obtain a best fit curve through the measured points and them normal vectors in order to compensate the radius of the probe.
However, during measurement of surfaces with edges and filets with radius less then probe radius discontinuities or deformations can occur in reconstructed profile (figure 8) [9].

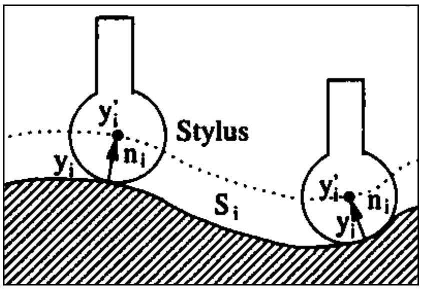
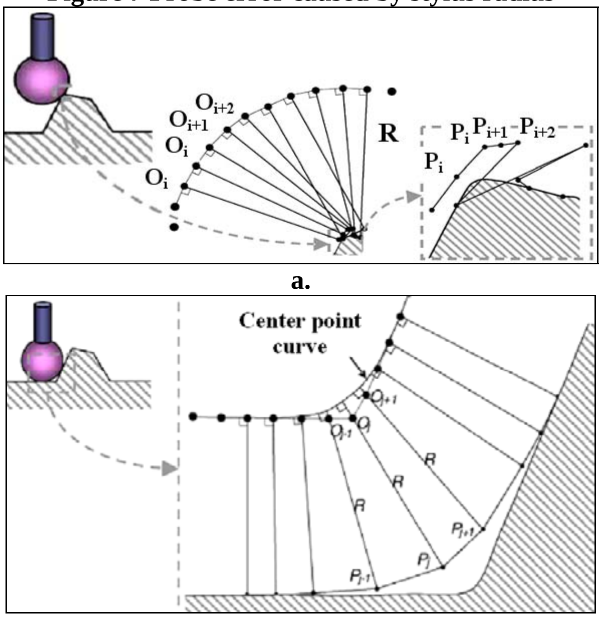


Figure 7 Probe error caused by stylus radius



a.

b.

Figure 8. The deviation of corrected measured points position resulting from wrongly estimated of normal vectors during correction of stylus tip radius

For point laser triangulation probe the main error sources are [5]:

➢ Color differences:

Because of intensity compensation, color difference of targets affect the measuring result only slightly, but such color differences, are often combined with different penetration depths of the laser light into the material, which result in apparent changes of the measuring spot size. Therefore color differences in combination with changes of penetration depth may lead to measuring errors. This fact also affects the linearity behaviour of the sensor, if it has been adapted for white diffusely reflecting reference material and is then used to measure black material. For to improve the linearity, the sensor must be optimised for the black material.

➢Temperature influences

When the sensor is used, a warm-up time of at least 20 minutes is required to achieve uniform temperature distribution in the sensor.
If measurement is performed in the micron accuracy range, the effect of temperature fluctuations on the sensor holder must be considered.

➢ Mechanical vibration

If the sensor should be used for resolutions in the µm to sub-µm range, special care must be taken to ensure stable and vibration-free mounting of sensor and target.

➢ **Surface roughness**
In case of scanning a roughnesses measurement surface appare an apparent distance change (also-called surface noise). However, they can be dampened by averaging.
➢ **Angle influence**
Tilt angles of the target surface, both around the X and the Y axis, of less than 5°, have a disturbing effect in the case of highly reflecting surfaces.
Tilt angles between 5 ° and 15 ° lead to an apparent distance change of approximately 0,12... 0,2 % of the measuring range (Table 1).
Tilt angles between 15 ° and 30 ° lead to an apparent distance change of approximately 0,5 % of the measuring range.
The angle influence depends also on the reflectivity of the target.

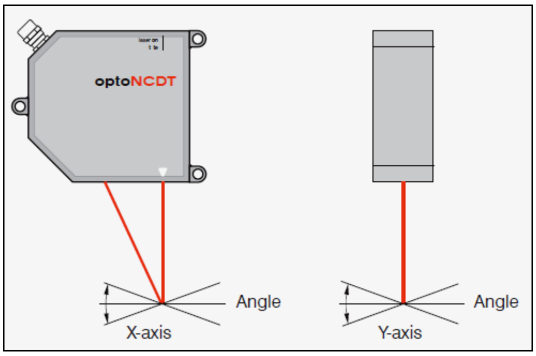


Figure 9 Angle influence

Table 1 Angle influence in measurement with point laser triangulation probe

Angle	X- axis %	Y- axis %
5°	typ. 0,12	typ. 0,12
15°	typ. 0,2	typ. 0,2
30	typ. 0,5	typ. 0,5

➢ **Sensor arrangement**
In case of rolled or polished metals that are scanned, the sensor plane must be arranged in the direction of the rolling or grinding marks.
When on the scanned surfaces there are holes, or grooves, the sensor must be arranged in such a way that the edges do not obscure the laser spot (figure 10).

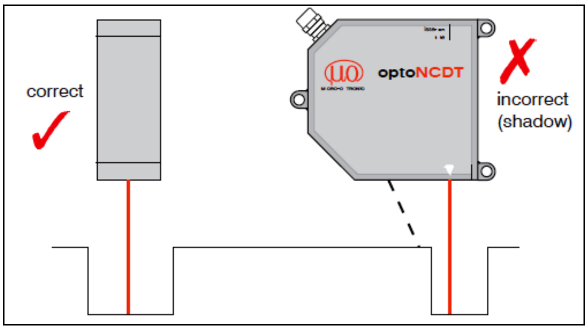
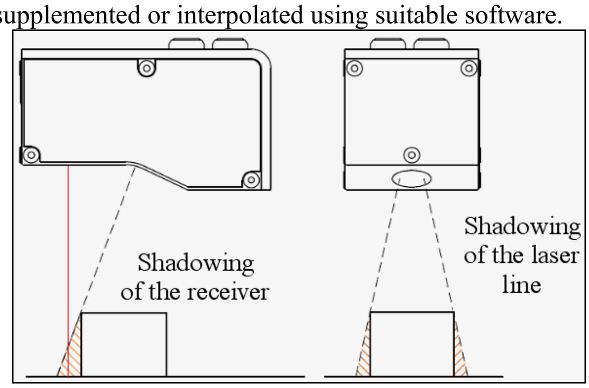


Figure 10 Sensor arrangement for surfaces with holes and grooves

For line laser triangulation probe the main sources of errors are [6]:
➢ **Reflection Factor of the Target Surface**
The sensor basically evaluates the diffuse portion of the laser line reflections. A preliminary evaluation is necessary for using the sensor on transparent or reflecting objects. The method of direct reflection on reflecting surfaces as it is successfully applied for the point triangulation cannot be used for the line triangulation. Here, the receiving lens would only be able to reach a narrow area near the center.
➢ **Color Differences**
Color differences of measurement objects, combined often with different penetration depths of the laser light into the material, results in apparent changes of the line thickness and in inaccurate measurements.
➢**Temperature Influences**
A running-in time of at least 20 minutes during start-up is required in order to achieve a uniform temperature spread in the sensor. For high accuracy of measurements the effect of temperature fluctuations on the mounting must also be observed by the user.
➢ **External Light**
The sensor has an interference filter for to suppress the external light. In general, the external light emission on the target or on the sensor must be avoided by using protective covers. To avoid unwanted reflections is recommended that all objects outside the measuring range to have matt black surface coatings.
➢ **Mechanical Vibrations**
For achieving the resolutions in the μm range with line laser triangulation probe, particular attention must be paid to the equipment stiffness and measuring object mounting.
➢ **Surface Roughness**
Surface roughness of 5 μm and more results in „surface noises" due to interference of the laser light.
➢ **Shadowing Effects**
The sensor must be arranged so as to avoid shadowing of the receiver or the laser line. The laser line can disappear completely or partially if the receiver is shadowed by step edges (figure 11.a). The fan-shaped form of the laser line results in partial shadowing at vertical edges (figure 11.b).
As a general rule, measuring objects with steep edges cannot be one hundred percent measured using laser triangulation. The missing areas can only be supplemented or interpolated using suitable software.



a **b**
Figure 11. Shadowing Effects

• **Computer system**

The computer system, including the control unit, involves both the hardware and the software. Errors in the hardware are not very common, therefore they will not be discussed. Errors in these calculation algorithms do occur and they can seriously affect and thus degrade the accuracy of the measuring result.
Besides the above mentioned related error sources, measuring accuracy is also influenced by external influences that can be related to the operator or the environment.
In our experimental task we will take in account all these error sources for to optimize the performances of this equipment.

5. CALIBRATION PROCEDURE

Calibration of the measurement equipment includes the calibration of positioning systems and sensors.
In our approach, calibrated objects with different types of geometry will be used for the comparison and verification of the accuracy of the 3D measurement systems. These calibrated objects are localized in well known positions relative to the equipment reference coordinate system and they are measured with scanning systems mounted on the longitudinal stage of the equipment.
By fitting the measured points to known information, the calibration parameters can be estimated.
The selected calibrated objects present the following geometric and dimensional characteristics:

- Caliber 1 - **Stepper caliber** (figure 12.a) - with horizontal step of approximately 9 mm and vertical steps of approximately 6 mm.
- Caliber 2 - **Variable radius cylinder caliber** (figure. 12.b) - with three controlled radius bearings.

A high precision CMM was used to obtain the height and length values of each step of the caliber 1 and the three radius values of the caliber 2 (Mitutoyo contact measure machine, Class 0, Precision 0,1 μm).

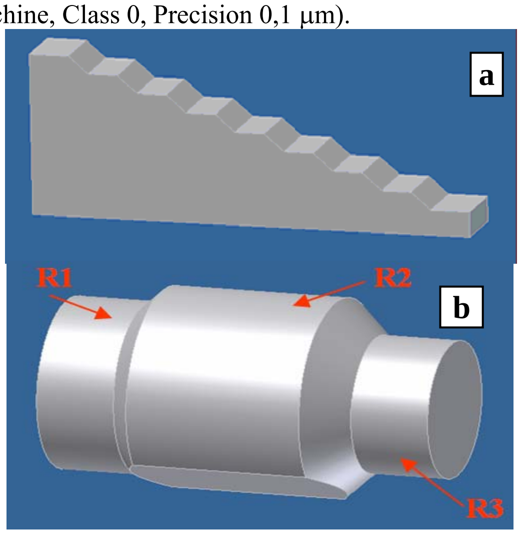


Figure 12 Calibers used in the calibration procedure: (a) stepper caliber, (b) cylindrical with variable radius caliber

6. CONCLUSIONS

This article presents design analysis of an equipment for free form surfaces measurement. This is a fixed bridge equipment with rigid structure. Its open architecture allows to attach, to modify and to replace components for adaptation to different conditions or tasks. It can be used for contact or non contact measurement of different types of surfaces (shiny, transparent or matte, rough or soft, with regular or irregular profile, with grooves or holes).
In the experimental task will be take in account all error sources for to optimize the performances of the equipment.
Expected performance:

- Measuring volume: X axes: 160 mm; Y axes: 150 mm (min. incremental motion = 0,1 μm); Z axes: 250 mm;
- Max. moving speed: X axes: 1 mm/sec;
  Y axes: 1,5 mm/sec ;
- Resolution: X axes: 0,1 μm ; Y axes : 0.0085 μm; Contact measurement sensor: 0, 5 μm; Point laser triangulation probe: 1,5 μm; Line laser triangulation probe: X axes: 128, 256, 512 or 1024 dots/ profile; Z axes: 10 μm

7. REFERENCES

[1] Wilhelmus Godefridus Weekers, Compensation for Dynamic Errors of Coordinate Measuring Machines, doctoral thesis, Technische Universiteit Eindhoven - Netherlands, 1996, ISBN 90-386-0178-6
[2] Sung-Chong Chung, CAD/CAM Integration of On-The-Machine Measuring and Inspection System for Free-Form Surfaces, Manufacturing Systems & Control Laboratory Department of Mechanical Design & Production Engineering Hanyan University, Seoul, Korea, http://www.aspe.net/publications/Annual_1999/ POSTERS/EQUIP/ANALYSIS/CHUNG_S3.PDF
[3] Kevin B. Smith, Yuan F. Zheng, Point Laser Triangulation Probe Calibration for Coordinate Metrology, Journal of Manufacturing Science and Engineering, Vol. 122, 2000, pp.583-585
[4] Kristine I. Spangard, New Advances in 3D Laser Scanning Technologies, Laser Design, Inc., http://www.laserdesign.com/upload/ docs/ new-advances-in-3d-laser-scanning_white-paper.pdf
[5] Micro-Epsilon, Instruction Manual, http://www.micro-epsilon.com/download/manuals/man--optoNCDT-22x0--en.pdf
[6] Micro-Epsilon, Instruction Manual, http://www.micro-epsilon.com/download/manuals/man--scanCONTROL-2700--en.pdf
[7] Ron Gershon, Meny Benady, Noncontact 3-D measurement technology enters a new era, http://www.qualitydigest.com/sept01/html/3d.html
[8] M. Ristic, I. Ainsworth and D. Brujic, Contact probe radius compensation using computer aided design models, Proc Instn Mech Engrs Vol 215 Part B, B12399, IMechE 2001, http://www3.imperial.ac.uk/pls/portallive/docs/1/44246.PDF
[9] A. Woźniak & J. R. R. Mayer & M. Bałaziński, Stylus tip envelop method: corrected measured point determination in high definition coordinate metrology, Int J Adv Manuf Technol (2009) no.42, pp 505-514.