WORKPIECE PROFILING USING LASER TRIANGULATION DISPLACEMENT SENSORS

FEKONJA, J., MUNDAR, G. & ZUPERL, U

Abstract: *The most important step in finalizing a production process is precise quality control of the manufactured product. For products manufactured with a high degree of precision, under strict tolerances, precise quality inspection is essential. In modern production, it is desirable for such processes to be accurate, reliable, repeatable, and above all, automated. Our work focuses on the design and development of a measuring cell, that precisely measures the surface roughness, and detects geometrical defects of a smaller workpiece, which was manufactured with a high level of precision and quality. For conducting precise measurements, the apparatus employs only a pair of displacement sensors, that measure a single point on touch-sensitive surfaces, using laser triangulation. Although such sensors are very accurate, their main drawback lies in the fact that they can perform measurements on only a single point. Thus, the measuring cell enables the sensors to move on the x and y axis, while also clamping the workpiece and allowing it to rotate to a desired position.*

Key words: *quality control, laser triangulation, displacement sensor, SICK, surface roughness*

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This Publication has to be referred as: Fekonja, J[ernej]; Mundar, G[oran] & Zuperl, U[ros] (2024). Workpiece Profiling using Laser Triangulation Displacement Sensors, Chapter 15 in DAAAM International Scientific Book 2024, pp.181-192, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734-42-6, ISSN 1726-9687, Vienna, Austria
DOI: 10.2507/daaam.scibook.2024.15

1. Introduction

In today's modern production, the manufacturing sector constantly strives for increased efficiency and superior product quality. For industries that operate under strict tolerances and produce quality goods on a large scale, precision and consistency in quality are essential. Thus, reliable detection of even the smallest imperfections, or manufacturing defects, which are unable to be detected with a visual inspection, can help in enhancing product quality. Defects in manufacturing can occur due to a variety of reasons, often resulting from a combination of factors like tool wear, material deficiencies and process variability. The result of these negative factors is a reduced quality of machined surfaces, which affects the accuracy of achieving the theoretically ideal dimensions of the workpiece. Inadequate or infrequent quality checks and inspections throughout the production process can significantly impact the functionality of a product (Yadav et al., 2022). One such defect, which we focused on detecting is poor surface finish of metal objects, which requires precise and non-destructive testing methods. Currently the most common method for surface inspection is visual inspection with digital image processing methods (Pernkopf & O'Leary, 2003) and machine vision systems (Ren et al., 2022). As industrial production continues to advance, the need for non-contact, real-time measurement of surface roughness has significantly intensified. This demand has been fuelled by technological progressions, specifically in laser technology, computer systems, and information processing. These advancements collectively enable highly precise surface measurements (Dong et al., 2018), meeting the escalating requirements of modern industrial processes.

Laser-based displacement measurement techniques have emerged as pivotal tools in modern industries due to their unparalleled accuracy, rapid data acquisition, versatility, and non-intrusive measurement capabilities. Due to their ability to accurately determine the distance of an object or surface, they're mostly used as non-contact probes for vibration analysis (Zhang et al., 2023), alignment or positioning and quality verification (Penttilä et al., 2022). The main drawback of laser triangulation sensors (LTS) lies in the fact that they can perform accurate measurements on only a single point on the surface, thus laser line scanners, are better suited for profiling (Sandak et al., 2020), because the distortion of the laser line on the object's surface is analysed at a high sampling frequency to capture the profile of the entire object (Sandak et al., 2020). Despite the ability of the laser profiler to produce a more comprehensive view of the object's surface, when compared to the pinpoint accuracy of the LTS, the result is a noticeably lower level of accuracy (Wieczorowski et al., 2019; Van Gestel et al., 2009). Thus LTS have the ability to perform surface roughness measurements (Dun et al., 2010).

Our work focused on the development of a prototype measuring cell, for precise profiling of a rotationally symmetric workpiece with a pair of SICK OD5000 displacement sensors in the SICK AppStudio development software package. Additionally, we explored the concept of utilising only two LTS to analyse the complete geometry and surface roughness of an object at a higher accuracy, than a laser profiler is capable of. Such a system could be used in CNC machines to provide real time on-machine measurements with which the quality of the manufactured workpiece could be determined (Ding et al., 2021).

The apparatus, which is constructed of aluminium profiles, works by centrically clamping the workpiece, while also allowing it to rotate to a desired angle along the x axis. Two LTS are perpendicularly directed towards the workpiece, which allows for conducting measurements of the top and side profiles. By linearly moving one of the LTS along the y axis at a constant speed, while the workpiece is spinning, precise surface profiling is achieved. Recorded data from both sensors is constantly compared to the theoretically ideal measurements of the workpiece, which allows for detection of certain defects, like eccentricity or surface damage on a microscopic scale. The position of both LTS may be adjusted according to the size of the measured object, since both sensors detect displacement in a positive or negative direction from a reference point in space, which is represented by a measurement of 0,00 mm.

2. Measuring methods

It was necessary to design and manufacture a measuring cell that would allow for adequate and centric clamping of the measured workpiece, while also allowing it to rotate to a desired angle of rotation when needed. Such a system would allow for conducting measurements along the entire geometry of the object. A solution for this was clamping the workpiece into a rotary chuck for a CNC lathe, the rotation of which was achieved by attaching a stepper motor to it. Both LTS needed to be attached to the apparatus in such a way, that would allow for movement of one of the sensors along the y axis, to be able to scan the geometry of the workpiece with a high accuracy. This was achieved by attaching the sensor to a linear motion guide with a stepper motor. It was also necessary for the measurement range of both LTS to be considered when determining the overall size of the cell. The measuring cell also needed to be constructed in such a way that would mitigate the vibrations caused by both stepper motors, since vibrations negatively impact the measuring accuracy of both LTS. The layout of the LTS and the cylindrical workpiece which is clamped in a lathe chuck is as shown in Fig. 1.

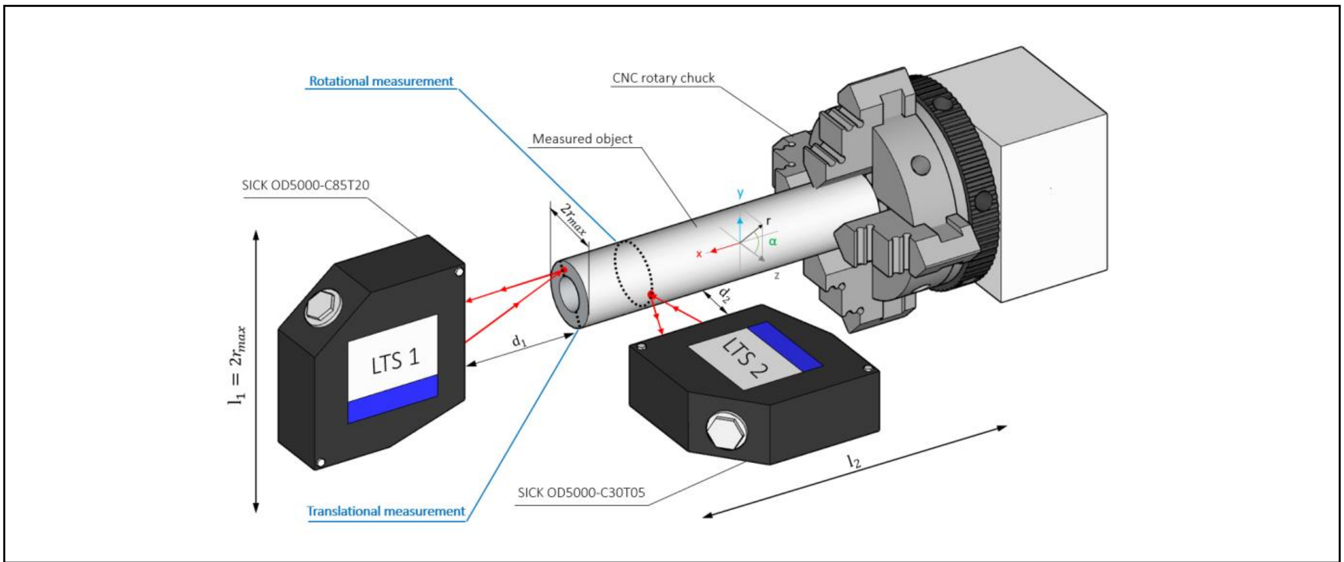

Fig. 1. Layout of LTS and workpiece.

For initial testing a hollow cylinder made of brushed steel was chosen as the measured object because of its simple geometry. In this layout two measurement methods are being conducted simultaneously. The measurement method where LTS 1 moves along the y axis at a constant velocity, while conducting measurements on a stationary workpiece is named as the translational measurement method. The second measurement method where a stationary LTS 2 measures the profile of the workpiece which is rotating at a constant speed is named as the rotational measurement. Both methods are described in the following subchapters.

2.1 Rotational measurement

To overcome the limitation of the LTS to be able to perform measurements on only a single point on a surface, the workpiece is centrically clamped, while rotating along the x axis at a constant speed. The LTS conducts a measurement on a microscopic level for every rotational increment of the stepper motor. The stepper motor is combined with a TB6600 Microstep driver. This allowed for the angle of rotation to be precisely controlled without the need of an incremental encoder and position regulation. Using a Microstep driver also allowed us to multiply the number of steps needed for a full rotation by a factor of 32. Since the recording procedure of the LTS is triggered for every rotational increment of the stepper motor, exactly 6400 measurements of the surface could be conducted per full rotation of the workpiece.

The SICK OD5000 LTS, as configured by default, operates by measuring displacement relative to a reference point set at 0,00 mm. In this setup, the reference point resides 30 mm away from the laser emitter within a measuring range of ±5 mm. The sensor and workpiece layout for this measurement method are depicted in Fig. 2.

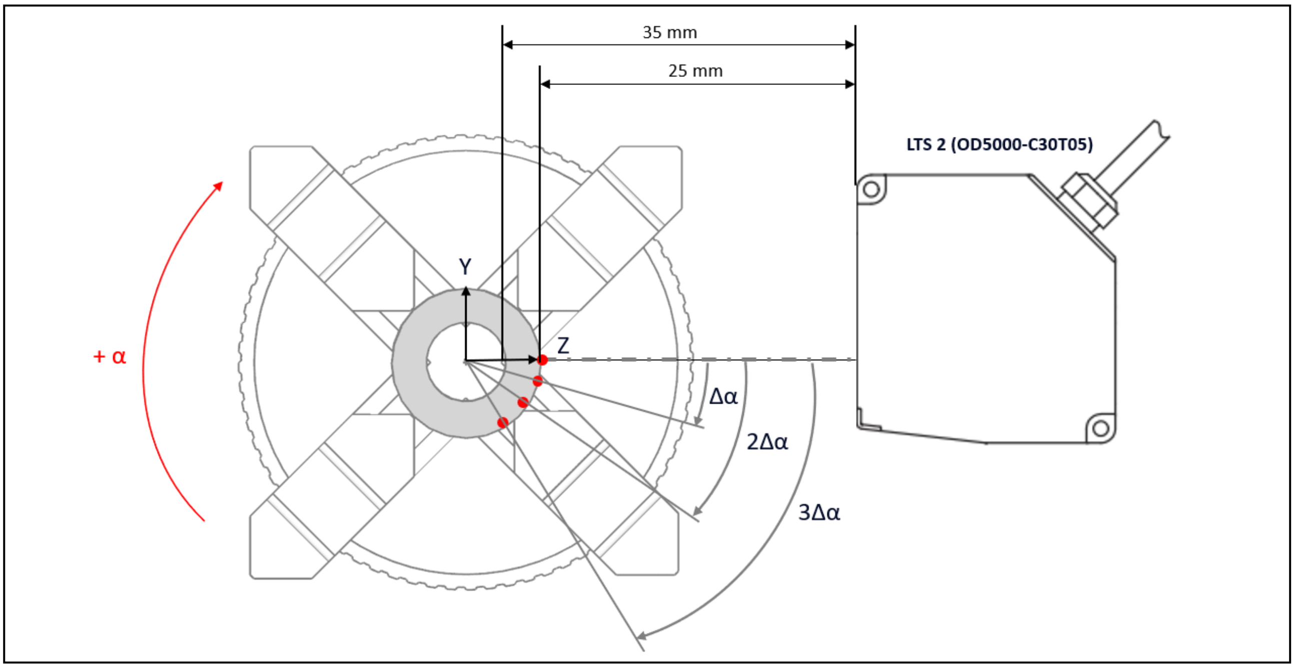

Fig. 2. Layout of rotational measurement method.

Surface roughness encompasses all surface irregularities perpendicular to a plane, typically measured in small increments over a distance of *l*.

Since the position of the LTS is along the z axis, and the sampling length *l* is the circumference of the workpiece, surface roughness may be mathematically evaluated. Fig. 3 shows the idea of calculating various surface roughness parameters via the center line average (CLA) method.

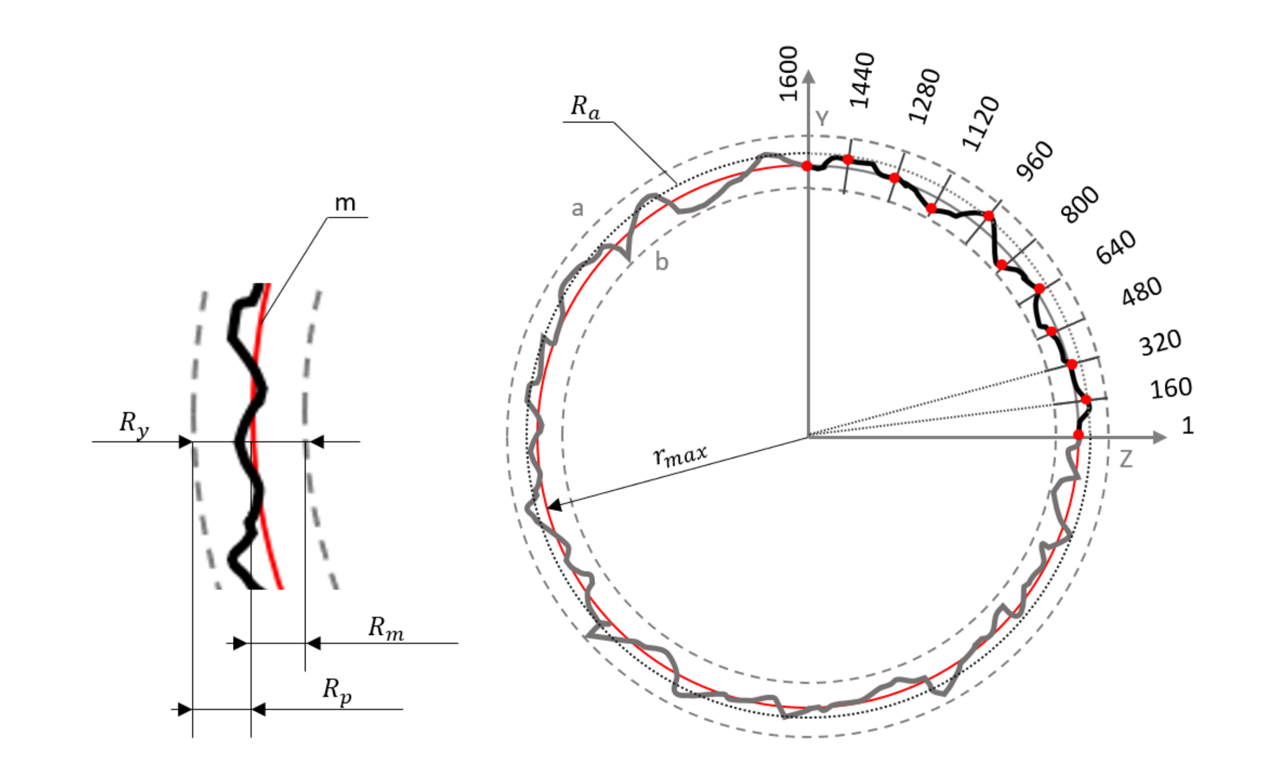

Fig. 3. Workpiece surface roughness via CLA method

Parameters *a* and *b* represent the highest and lowest measured point respectively. The centreline *m* is represented by the radius of the workpiece r_max. The arithmetic mean deviation R_a of the profile represents the average of the absolute values of the profile's deviations within the sampling length *l*. R_a *c*an approximately be calculated with equation 1:

$$R_a \approx \frac{1}{n} \sum_{i=1}^{n} |z_i| \tag{1}$$

Where *n* is the number of measurements along the z axis, which in our case is n=6400. The system may also calculate the profile height over ten points R_z by detecting five of the highest and lowest points along the sampling length *l*. R_z is calculated with equation 2:

$$R_z = \frac{\sum_{i=1}^{5} |y_{pi}| + \sum_{i=1}^{5} |y_{vi}|}{5} \tag{2}$$

Where y_{pi} represents the i-th highest point in the positive direction of the z axis, and y_{vi} is the i-th lowest point in the negative direction.

In accordance with specific quality criteria, the measuring cell features a pre-established tolerance zone around the workpiece surface.If successive measurements consistently surpass this tolerance zone, a defect is detected, and the workpiece is discarded. Combined with the ability to measure the surface roughness, the end quality of the workpiece can be evaluated.

2.2 Translational measurement

The second measurement principle employs the SICK OD5000-C85T20 LTS to profile surfaces, detect edges, and assess surface roughness on a cylindrical workpiece. To enhance the LTS capabilities beyond single-point measurements, the sensor is affixed to a linear motion guide, oriented perpendicular to the stationary workpiece. The linear motion guide, powered by a stepper motor, moves the sensor uniformly upward along the y axis during the measurement process. As the sensor ascends, it scans the workpiece surface, conducting measurements every time a set number of increments of the stepper motor have occurred.

In this setup, the nil reference point of the SICK OD5000-C85T20 LTS resides 85 mm away from the laser emitter within a measuring range of ±20 mm. The sensor and workpiece layout for this measurement method are depicted in Fig. 4.

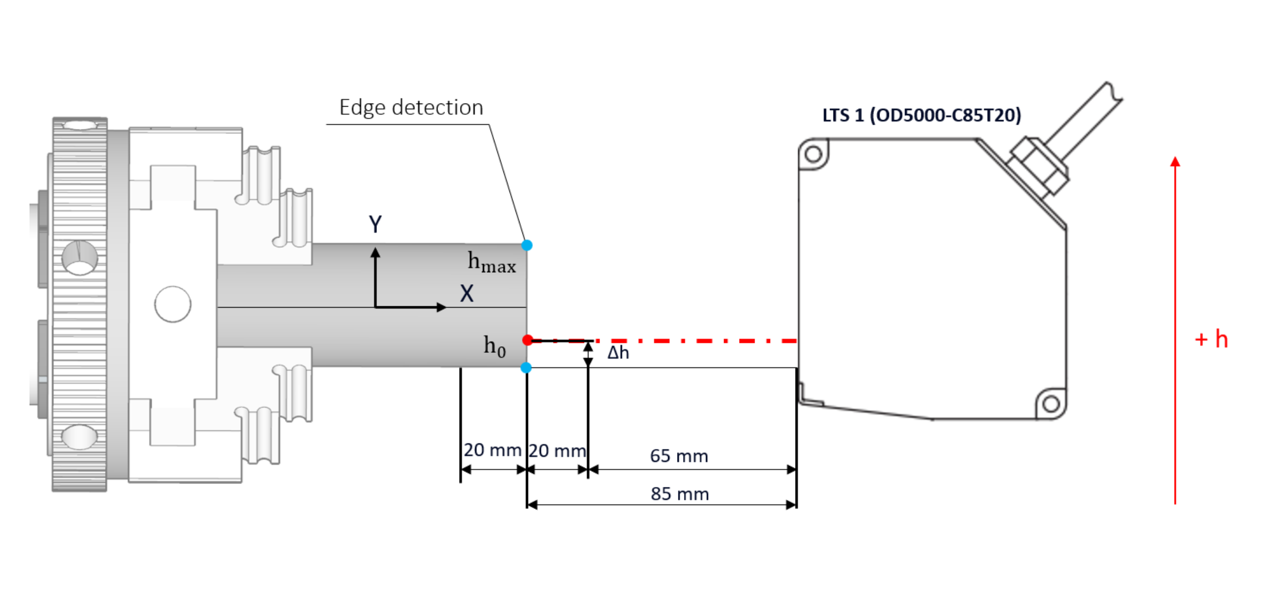

Fig. 4. Layout of translational measurement method.

When the LTS reaches the top of the workpiece (h_{max}) in the +y axis, and exceeds its measurement range, an interrupt routine is triggered. In this routine, recorded data is saved, and surface roughness is evaluated using the CLA method with equations (1) and (2). Throughout this process, the LTS remains stationary, while the workpiece rotates to a new position defined by the rotation angle α. The LTS changes direction and scans the workpiece surface in a downward direction along the -y axis. This process of reversing the direction of the LTS repeats every time the sensor goes out of range. The more passes over the object's surface, the more comprehensive the overview of the object's geometry becomes.

During the measurement process, measured data is constantly being compared to the theoretically ideal dimensions of the workpiece. If successive measurements consistently surpass this tolerance zone, a defect is detected, and the workpiece is discarded. Fig. 5 shows the measurement process of the translational measurement method.

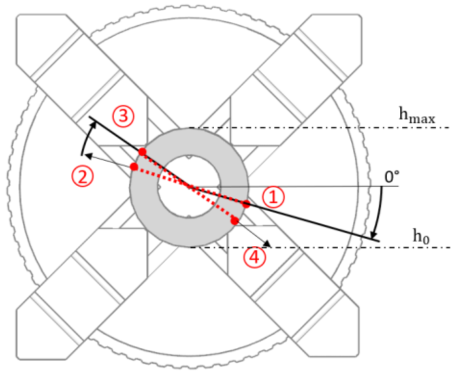

Fig. 5. Translational measurement method process.

3. Measuring cell

In designing the measurement cell, we considered the requirements from earlier chapters. The machine securely clamps the workpiece, with a rotational rotary axis, allowing rotation along the x-axis. The LTS 2 moves along the y-axis using a linear motion guide powered by a bipolar stepper motor, while the second sensor is affixed to a rail, allowing manual movement of the LTS along the x-axis. To address vibrations, caused by stepper motors which can negatively impact the final measuring accuracy, we opted for a sturdy construction using 40x40 aluminium profiles. We also factored in the measuring range of both sensors in the design, which allowed the machine to measure workpieces up to 40mm in length and 20mm in diameter. The sensors and stepper motors are controlled by the SICK SIM4000 sensor integration machine, which was programmed in the AppStudio software package. The actuators are controlled via the I/O ports, while the sensors communicate via Ethernet UDP/IP protocol. The measurements are displayed on a PC which is connected to the SIM4000. The 24 V power supply provides power for the SIM4000, stepper motors and sensors.

3.1 Hardware

The assembled system consists of the following hardware:

- SICK OD5000 C30T05 and C85T20 Laser triangulation displacement sensor
- SICK SIM4000 Sensor Integration Machine
- Linear motion rail with NEMA 17 stepper motor
- Rotary chuck with NEMA 23 stepper motor
- TB6600 Microstep driver
- 24 V power supply

3.2 Measuring cell design

The 3D model of the machine was created in the SolidWorks software tool based on the requirements of the used hardware. Coherent with the layout of the sensors and workpiece in Fig. 1. the 3D model is as shown in Fig. 6.

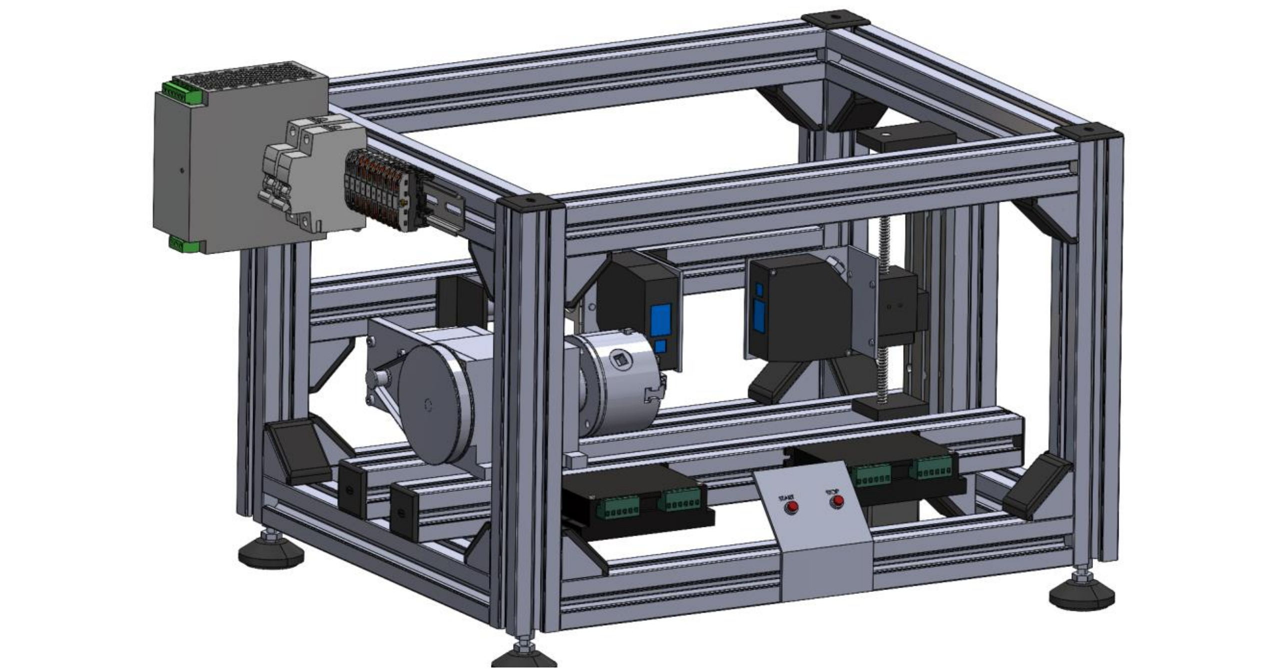

Fig. 6. 3D model of the measuring cell

Fig. 7. shows the implementation of the measuring system. Both LTS are performing measurements on a stainless-steel cylindrical workpiece, which is centrically clamped in a rotational rotary axis with a 4-jaw chuck.

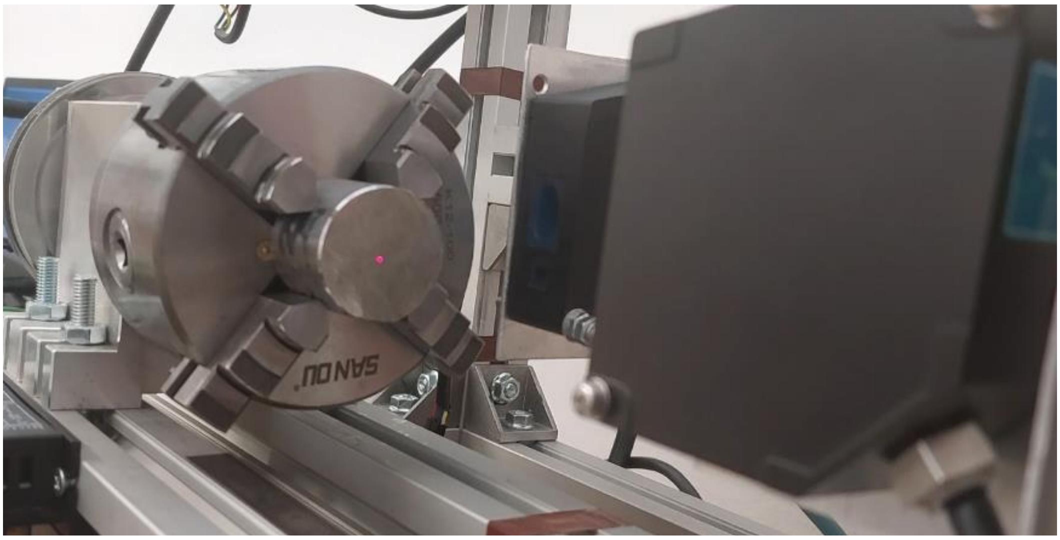

Fig. 7. Actual measuring system

3.3 Rotary axis

The rotary axis with a 4-jaw chuck is a mechanism we used to centrically clamp and rotate irregularly shaped workpieces, as it allowed for performing multi-axis measurements, enabling the LTS to access different surfaces on the workpiece.

The mechanism uses a 2-phase stepper motor, which spins the chuck via a belt drive with a 6:1 reducing ratio. The step angle is 0.3 degrees/step, which allowed for open-loop control and accurate positioning. This flexibility was crucial for ensuring proper alignment and stability during the measuring process. There is no need to manually adjust the position of the rotary axis, if the workpiece is in range of both LTS.

3.4 Sensor mounts

The motion of both LTS units was achieved using a round guide for LTS 2 and a linear motion drive for LTS 1, both securely affixed to the machine housing. The round guide allowed for manual adjustments of the position of LTS 2, as the sensor remained stationary during the measuring process. LTS 1, on the other hand, was mounted on a ball screw trapezoidal linear motion drive powered by a stepper motor. A linear motion guide was selected for its position accuracy of ±0.01 mm, as well as its straightforward lightweight design, open-loop control capabilities, and minimal vibrations during operation. Fig. 8 shows the sensor mounts and their stroke range.

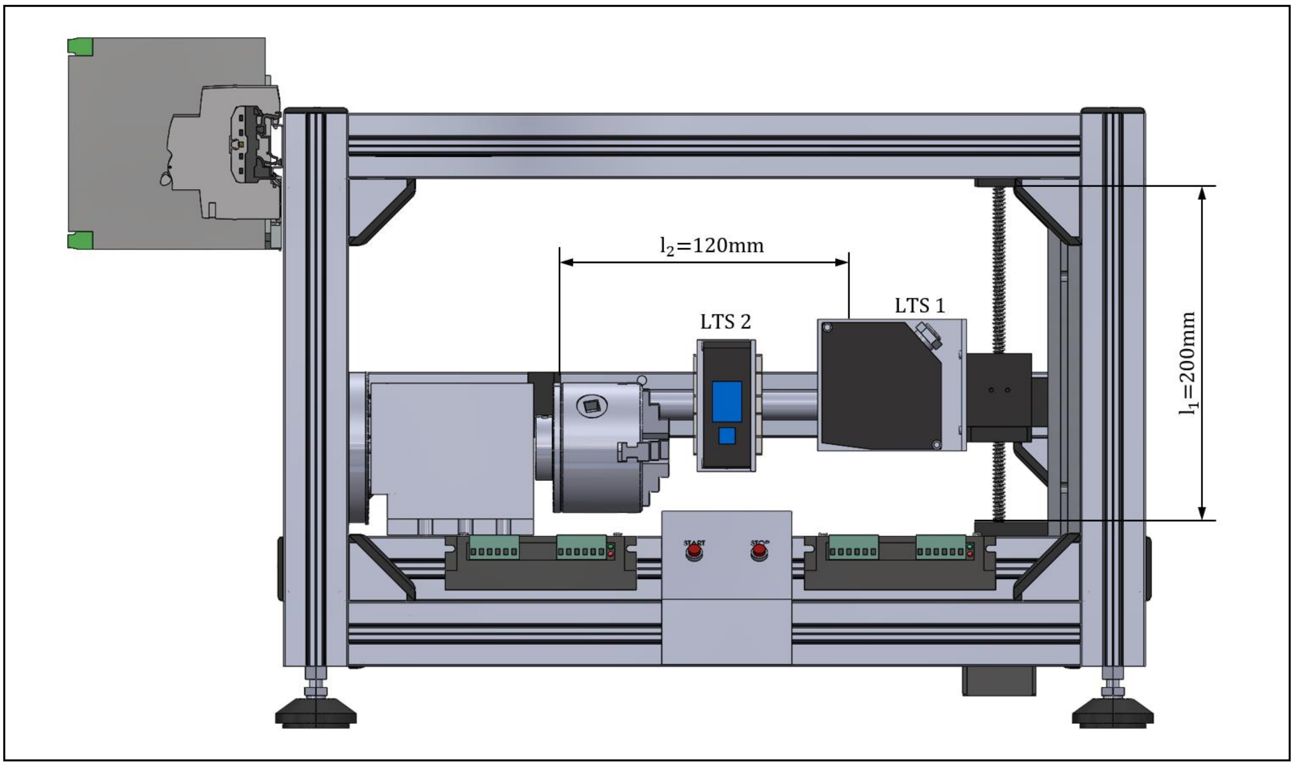

Fig. 8. Stroke range of LTS 1 and LTS 2

4. Results

Initial tests of LTS were performed by utilizing the integrated measurement and diagnostic interface, SopasAir. The interface allowed for real-time measuring and data acquisition by establishing a connection between the LTS and a PC through Ethernet with the UDP/IP communication protocol. The goal was to assess both the precision and repeatability of measurements, along with evaluating the accuracy of edge detection.

In Fig. 9, the plot illustrates measurements of LTS 2 taken over a 20-second interval using rotational measurements obtained via SopasAir. The test was conducted on a finely brushed cylinder, that was spinning with a rotational frequency of 0,5 Hz. The recorded measurements hover around the 6 mm mark. This is attributed to the LTS being positioned 19 mm from the cylinder's surface, detecting a displacement of +6 mm. The sinusoidal characteristic of the graph is a result of the cylinder's slight eccentricity. Notably, the measurements exhibit an accuracy within the range of ±4 μm, which is still a noticeably lower level of accuracy than the sensor is capable of.

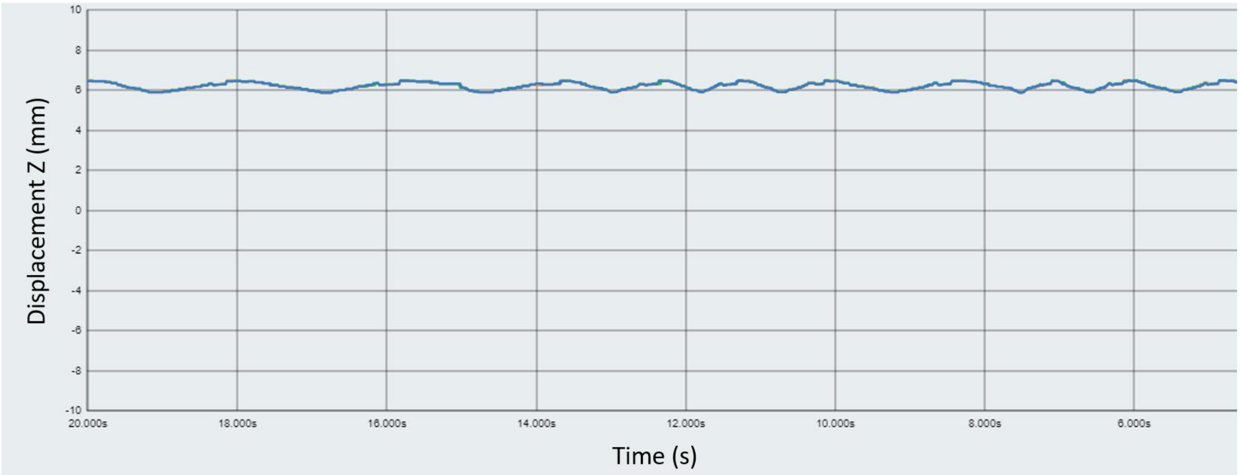

Fig. 9. Measurements performed with LTS 2

Fig. 10 depicts the LTS 1 measurements captured over a 20-second span using the translational method. In this test, the LTS traversed the surface of the cylindrical workpiece at a consistent speed of 2.5 cm/s. Simultaneously, the workpiece rotated by 60 degrees each time the LTS detected its edge, which is apparent by the time of rotation Trot. The goal of this test was to evaluate the accuracy of edge detection, revealing that the measurements demonstrate precision within the range of ±10 μm.

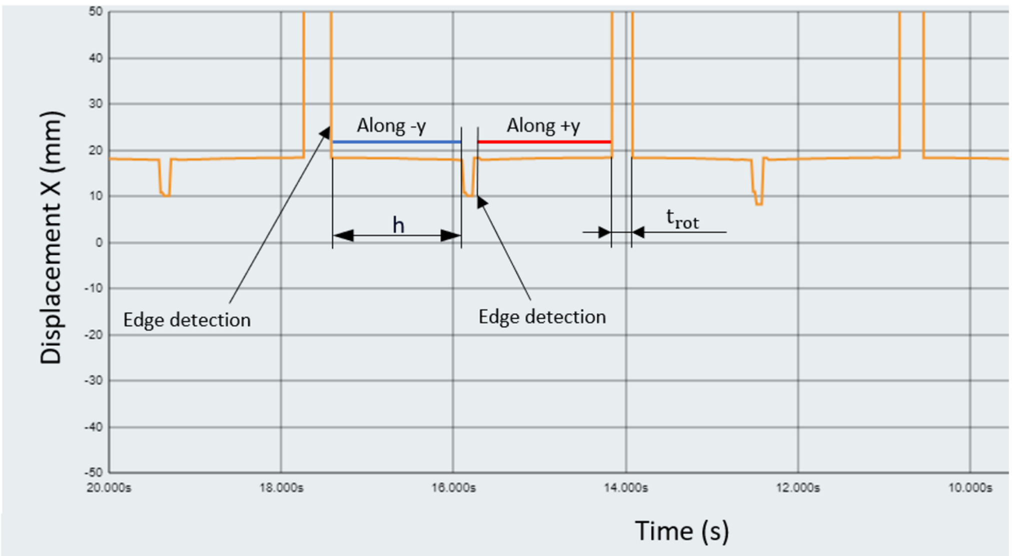

Fig. 10. Measurements performed with LTS 1

5. Conclusion

The primary problem addressed in this research was the need for precise quality control in the production of rotationally symmetric workpieces, specifically in detecting surface roughness and geometric defects with high accuracy. To solve this, we developed a prototype measuring cell utilizing two high-precision laser triangulation sensors (LTS) for real-time non-contact measurements. These sensors were integrated into a system capable of automatically profiling the surface of workpieces during the manufacturing process.

The results of the testing showed that the system achieved an accuracy of ±10 µm in surface profiling, which, while lower than the maximum potential accuracy of the sensors (±0.1 µm), is still suitable for many industrial applications. The solution effectively enables the detection of microscopic surface defects and geometric inaccuracies, providing a significant improvement over traditional methods.

While the prototype met its initial objectives, several limitations remain. For instance, the device's open-loop control and the presence of vibrations during measurement affected the precision. These issues indicate opportunities for further refinement, including the addition of feedback control systems and vibration damping mechanisms.

Looking ahead, future work will focus on optimizing the system’s accuracy by addressing the identified weaknesses. The incorporation of a feedback loop and enhanced clamping mechanisms will allow for even greater precision. Additionally, implementing this system in CNC machines for real-time defect detection and tool wear monitoring will significantly enhance manufacturing quality control.

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