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Principal investigation for the application of structured light scanning for the measurement of thickness using differential measurement method

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Abstract. As an industrial approach, structured light scanning is an established technique to handle length measurement by using light as information carrier and a CCD sensor to acquire that data into the digital domain. By means of triangulation, contours can be scanned and initiating uniquely defined relative movements of the object add another dimension. So it is possible to scan surfaces as well. That technique is basically known by scientists and manufactures. However, the very high application diversity leads to problems that needs good engineering and interdisciplinary work. The aim of this paper is to explain how structured light scanning could deal with complex objects like elastic and quite flexible materials. To examine if that approach is principally possible and how uncertainties are scalable is the primary purpose. Furthermore, that fact and the measuring principle itself requires well-considered approaches in calibration, adjustment, data management until a needed construction to minimalize expansions and keep that system working stable within industrial environments.

1. Introduction, state of the art and short system description

Image processing is one of the key technologies for optimization of industrial processes, the option for 100% quality assurance and many other essential industrial and research topics. Not least, by regarding the central ideas and the spirit of internet of things, applications featured image processing are omnipresent. A major application is the acquisition of projected structured forms, such as lines and other shapes. The geometrical conditions to use the concept of triangulation are complied with a two-dimensional CCD camera and a laser line [1],[2]. The aim of this concept is to get three-dimensional information by projecting a line as a shape on an object. On condition that distance and triangulation-angle being known, a function to calculate height can be defined. By relative movement between probe and structured illumination, it is possible to acquire surfaces and other 3D-informations. Assuming the object is symmetrical (or only one surfaces is the point of interest), the concept of one triangulation system works fine. However, if the object is unsymmetrical to the plain that was defined after calibration, information would be lost while the object covers partially his shape himself. Due this work, the outline of a cutaway view is the point of interest, provided that prismatic or cylindrical shapes are also manageable. So, it is necessary to apply the concept of differential measurement.

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2. Experimental setup and measurement principle

A schematic view of the experimental setup is given in Figure 2. In this case, two triangulation systems are required to practice differential measurement. The basically needed components are: (1)-upper CCD camera, (2)-lower CCD camera, (3)-flexible sample, (4)-upper laser and (5)-lower laser. To find the optimal extensions, dimensions and triangulation angles of the setup and its components depending on the sample geometry is also part of the investigation. Due to a specific industrial demand, the working distance between the laser source and the calculated reference plane should be scalable up to one meter as maximum.

Figure 1. Possible sample geometry.

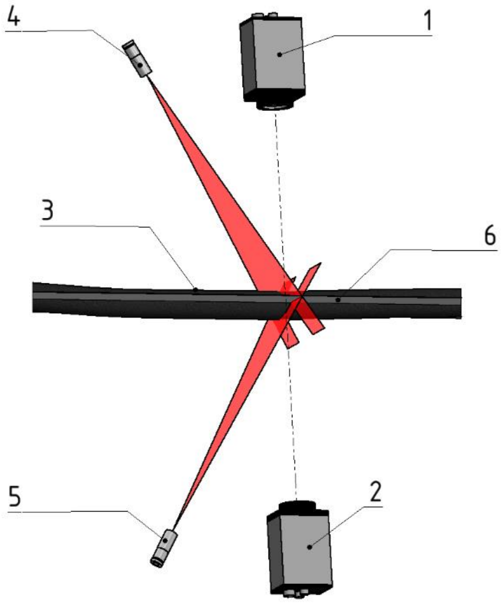

Figure 2. Experimental schematic view.

Figure 1 shows a possible sample geometry that represents properties of the interesting objects. In this example, the cross-section profile is elliptical, but longitudinally not constant, what means that it sweeps on a not linear path. This circumstance is a succession of flexibility in material and causes another relative movements. The advance against the triangulation system must be respected in the incoming signal processing as well. With respect to a working distance up to one meter, it is necessary to observe special laser light sources, which insure a much as is necessary accurate laser line with minimal diverging optical behaviour in the projected contour as well. Additionally, results of researches show that, regarding to adjustments in laser linewidth, off the shelf laser light sources and optics are insufficient. Therefore, the required linewidth is not realizable without additionally optical instruments. So, another research in this publication deals with modulations inside the optical path to make that linewidth adjustable. Figure 3 to Figure 5 shows some chosen approaches to design the optical path. To rank them, it is necessary to compare the individually advantages and disadvantages. One first simple solution is to convolve the optical path by integrating mirrors. The light source must produce a orthogonal linear laser beam by itself. Changing angles and distances in this setup leads to adjustments in line width. But respecting the experimental setup, approximately calculated geometrical extensions

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show that this solution is not practicable for that investigation. The necessary diameters of that mirrors need too much space, especially by the fact that to optical systems are needed.

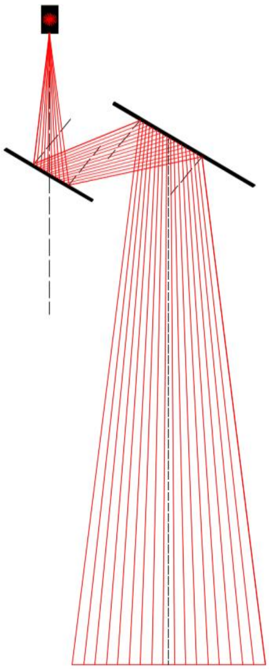

Figure 3. Convolved optical path.

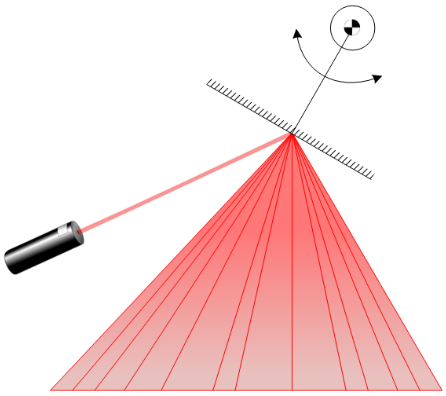

Figure 4. Modulated by oscillating plane mirror.

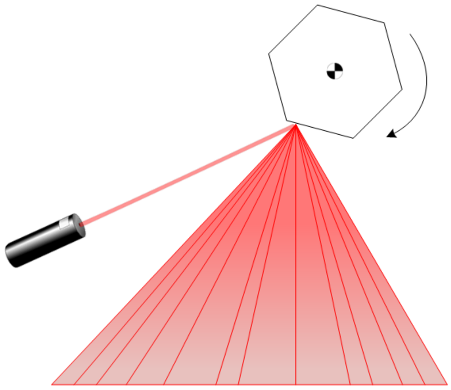

Figure 5. Modulated by rotating hexagonal polygon mirror.

The system shown in Figure 4 produces the laser-line by direct a point-like laser source at a one direction oscillating plane mirror. A main disadvantage of this system is that the actor must also be oscillated. Consequently, much attrition appears and pulsed signals must be produced and initiated too. Another disadvantage is the (mechanical) limited frequency that leads to limitations in variation of the integration time of the CCD-cameras. The third approach, shown in Figure 5, is to focus a point-like laser source at a continuously rotating hexagonal mirror. That system have nearly the best preconditions to be integrated in the explained experimental setup. By using a brushless DC motor, less attrition appears and repetition time could be manipulated by modifying rate of rotation. Standard laser diodes could be used as a low-cost light source. A simple electrical actuator is schematically shown in Figure 6. Only one voltage source is required to supply all components with electrical energy. A few different stages are needed to control all components too. A major advantage of this approach is that it is long-term stable, easy to adjust and a high laser line length could be realized by using few components.

3. Principle required calculations for the method of measurement

All needed trigonometrical basics are shown in Figure 7. Transferring that relationships into analytical formulas leads to an expression that contains the parameter of interesting z_p as a function of two different linear displacements x_1 and x_2 and the triangulation angles α_1 and α_2.

$$z_p(x_1, x_2, \alpha_1, \alpha_2) = \frac{x_1}{\tan \alpha_1} + \frac{x_2}{\tan \alpha_2} \tag{1}$$

Assuming that uncertainties in distances are included in the angles, the significant uncertainty is theoretical dependent by the pixel-scales dx_1 and dx_2 and the two triangulation-angles and can be approximated [3] by using:

$$dz_p = \frac{1}{\tan\alpha_1}dx_1 + \frac{1}{\tan\alpha_2}dx_2 + \frac{x_1}{(\tan\alpha_1)^2\,(\cos\alpha_1)^2}d\alpha_1 + \frac{x_2}{(\tan\alpha_2)^2\,(\cos\alpha_2)^2}d\alpha_2 \qquad (2)$$

For a reliable contour representation within production process, it is necessary to have an intelligent and stable working signal processing concept. Based on reference values, which result from calibration with a calibration object, the system must be adjusted. Therefore, it is possible to compare all the real-time data with a reference model to compute the real shape of the cutaway contour. Finding an acceptable calibration model is also part of the investigation and annotated in chapter 4. An overview of the principle necessary computing steps is given in Figure 8. Based on the elliptical example that is given in Figure 1, Figure 8 (a) shows the separate acquired shapes.

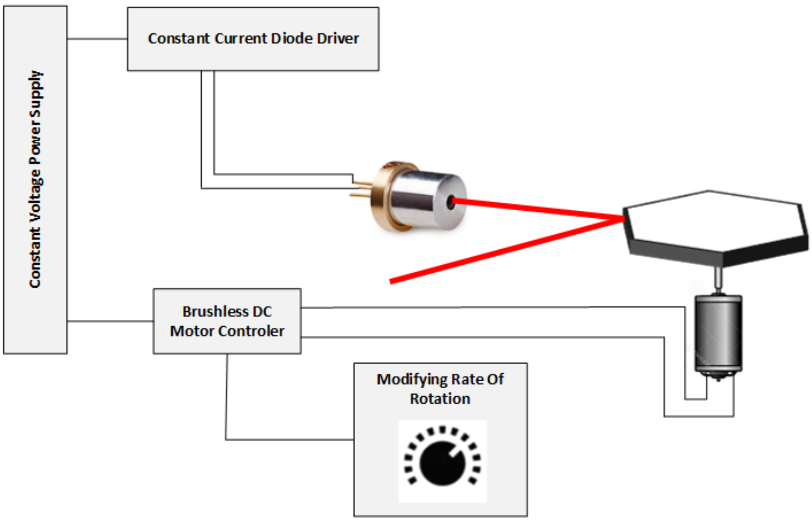

Figure 6. Electrical components.

Firstly, the difference must be computed, perhaps by applying operations and affine transforms like rotating or stretching relatively [4]. The combined result is shown in Figure 3 (middle). Secondly, static parameters from the triangulation system are used to reproduce the real contour by adapting the defined function. The final result is shown in Figure 3 (right). With respect to fast image processing, it is necessary to develop efficient algorithms - minimizing computing time is also an aim. So, the correction algorithms were programmed as efficiently as possible [5] . Furthermore, the basic concept of the affine transformation– showed in chapter 4 - will be explained. The main property of an affine transformation is that a point will be mapped to a point and a line will be mapped to a line. Respected to homogeny coordinates $(x, y, 1)^{\mathrm{T}}$, the following transformation matrices will be used [3] :Displacement in x by respecting parameter a, displacement in y by respecting parameter b:

$$M_{a,b} = \begin{pmatrix} 1 & 0 & a \\ 0 & 1 & b \\ 0 & 0 & 1 \end{pmatrix}. \qquad (3)$$

Rotating against the origin by respecting angle α:

$$M_{\alpha} = \begin{pmatrix} \cos(\alpha) & -\sin(\alpha) & 0 \\ \sin(\alpha) & \cos(\alpha) & 0 \\ 0 & 0 & 1 \end{pmatrix}. \qquad (4)$$

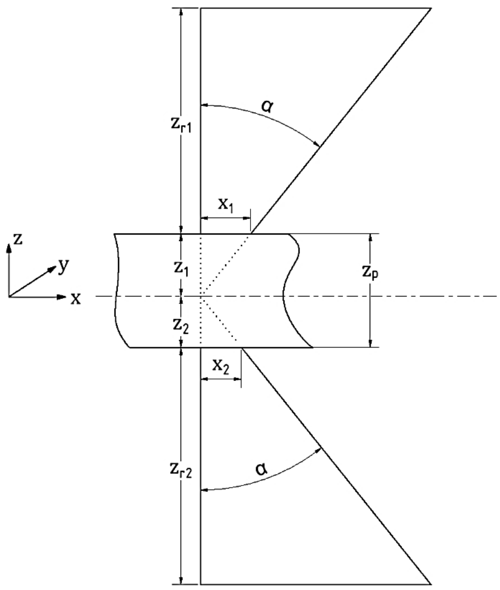

Figure 7. Trigonometrical relationships of differential measurement by triangulation.

The complete affine transformation matrix results by multiplying $M_{a,b}$ and M_{α} .

$$M_{affine} = \begin{pmatrix} 1 & 0 & a \\ 0 & 1 & b \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \cos(\alpha) & -\sin(\alpha) & 0 \\ \sin(\alpha) & \cos(\alpha) & 0 \\ 0 & 0 & 1 \end{pmatrix}. \quad (5)$$

Finally, the needed affine transformation can be done by multiplying each (homogeny) pixel coordinate with the affine transformation matrix:

$$I_{pixel,transformed} = I_{pixel} * M_{affine} = \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & a \\ 0 & 1 & b \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \cos(\alpha) & -\sin(\alpha) & 0 \\ \sin(\alpha) & \cos(\alpha) & 0 \\ 0 & 0 & 1 \end{pmatrix}. \quad (6)$$

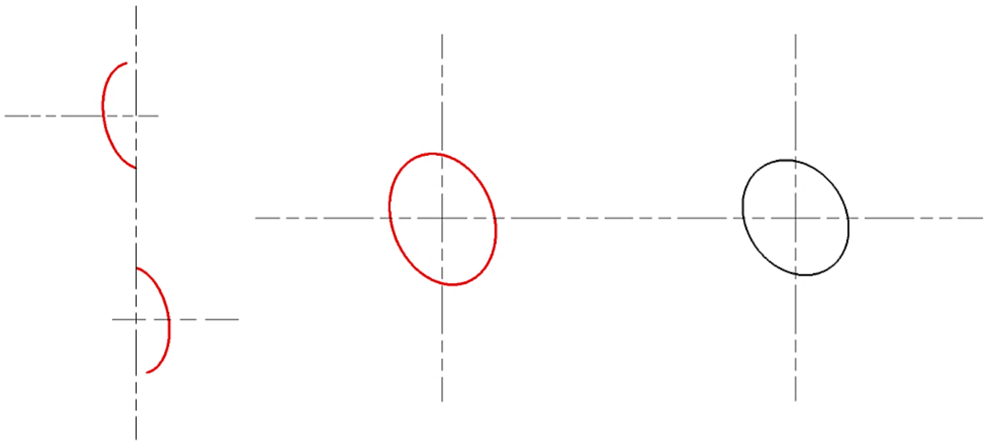

Figure 8. Separate shapes from upper and lower CCD (a), combined shapes after correction (b), finally calculated shape (c).

In addition, it is obvious that it is necessary to iterate that calculation with all pixels to get the complete transformed image I' .

$$\sum I'(x_i, y_i) = \sum\left[I(x_i, y_i) \cdot M_{affine}\right] = \sum\left[\begin{pmatrix} x_i \\ y_i \\ 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & a \\ 0 & 1 & b \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \cos(\alpha) & -\sin(\alpha) & 0 \\ \sin(\alpha) & \cos(\alpha) & 0 \\ 0 & 0 & 1 \end{pmatrix}\right]. \quad (7)$$

4. Image processing, adjustment and calibration concept

Assuming that both cameras are displaced, it is necessary to adjust each other. One camera (i.e. the upper one) is selected as a reference camera. In this investigation this task should be done by software adjustment. That procedure is detailed shown in Figure 9. Initially, static pictures was acquired by both cameras. Based on this pictures, images undergoes edge detection to subtract them later from next pictures including a first calibration object. The first step is to bring in a physical reticle inside the optical path. Secondly, the both pictures undergoes separately edge detection again. After adding those pictures and subtracting the initial taken static pictures, the result contains all information that was necessary to adjust. In the next step, gaps in the lines were filled by interpolation. In the calibration step, the two intersections of every reticle are computed and set to an initial defined reference point which represents the basic Cartesian point of origin and the rotation point for all following steps. Furthermore, all parameters (rotation angles, linear displacement values) that are necessary to apply affine transformations can be computed and combined to an image rectification matrix. That matrix contains all transformation information for each camera channel. Therefore, both pictures can be rectified separately. After the image rectification matrix is deposited, the first calibration procedure is completed. The third and last procedure is to find and correct the displacements of the two projected laser lines. This can be done by bringing in a rectangular calibration object with known thickness inside the optical path. The displacement occurs as a non-parallelism and could be detected by using the first calibration procedure again, but now with focusing on the laser lines. Therefore, both fitted line vectors have an intersection. Its vertical value must be compared by that of the real calibration object and the resulting difference is the coefficient to correct the vertical displacement. By correcting the point of origin this way, the Cartesian coordinate system is now scaled to calculate thickness information. Therefore, the abscissa is set as a zero order reference.

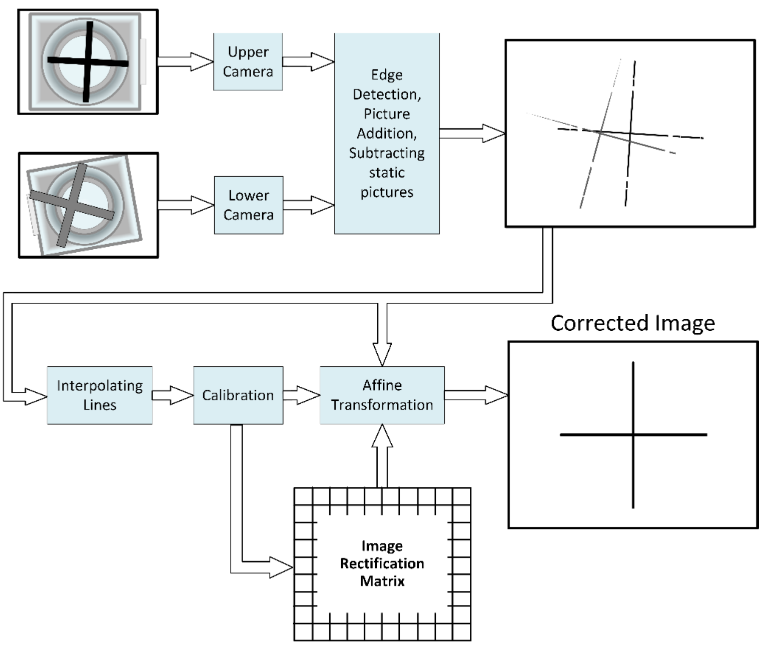

Figure 9. First calibration procedure to getting affine transformation parameters.

Additionally, the value must be deposit as a transformation parameter in the extended image rectification matrix as well. Now, the reference-plane is shown in Figure 2 (6). The last step is to equalize the parallelism of the two lines by finding the rotation angles against the corrected Cartesian coordinate system and deposit them in the extended image rectification matrix as well. Finally, the lines can be corrected by applying the affine transformation including the extended image rectification matrix. This procedure is exemplarily shown in Figure 10. Annotating, the maximal distance between that two straight lines inside the area of interest is a systematic error caused by warping profile and ignoring a physical area of material.

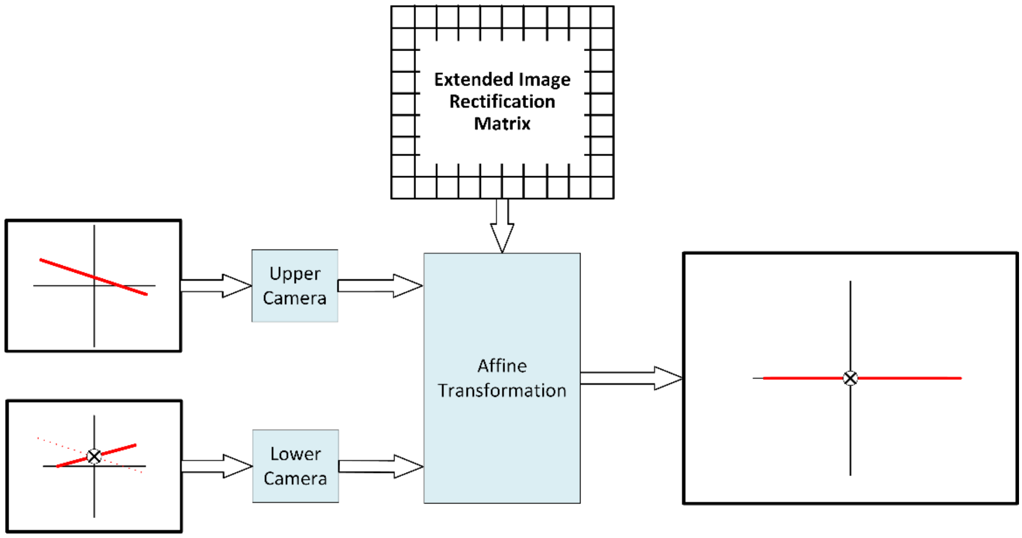

Figure 10. Equalizing the parallelism of the two laser lines.

5. Measurement data and discussing uncertainty

Uncertainty caused by pixel size could be evaluated by consulting the datasheets of the used optical equipment. Another method is to compute pixel-scaling by using a 2D chess-pattern, which was applied in that first prove of concept. By shifting that pattern inside the optical path (orthogonal to the optical axis) it is possible to develop a correcting-polynomial to scale optical parameters as well. That practice is useful if the objective is not telecentric. Beside the fact of systematic uncertainty caused of the pixel size, all the rest influences are coded in the angle. By respecting the complexity, it was not possible to estimate, all (geometrical) uncertainty in that investigation. The given data was calculated by trigonometrical values estimated with a calibration object. Therefore, the uncertainty of other trigonometrical parameters coded in that triangulation angles could not be discussed in that investigation.

Figure 11 shows the data which was taken in that prove of concept. All previously mentioned concepts, such as affine transformation and image rectification was applied after capturing that data. The object in that image has a rectangular shape with the dimension of 20 x 20 mm. That simple shape was used to get calibration-data as well. So it is obvious that both sides fit in the 10 mm lines relatively well. Additionally, there is a groove at both sides that decreasing thickness from 20 mm to 5 mm . Focusing that grove, the upper measurement deviation amounts to 1.21 mm average and the lower measurement deviation amounts to 1.76 mm average. Both values are not satisfying for precision measurement applications. Furthermore, experiments done with other materials offers that deviations increasing by enlarging thickness.

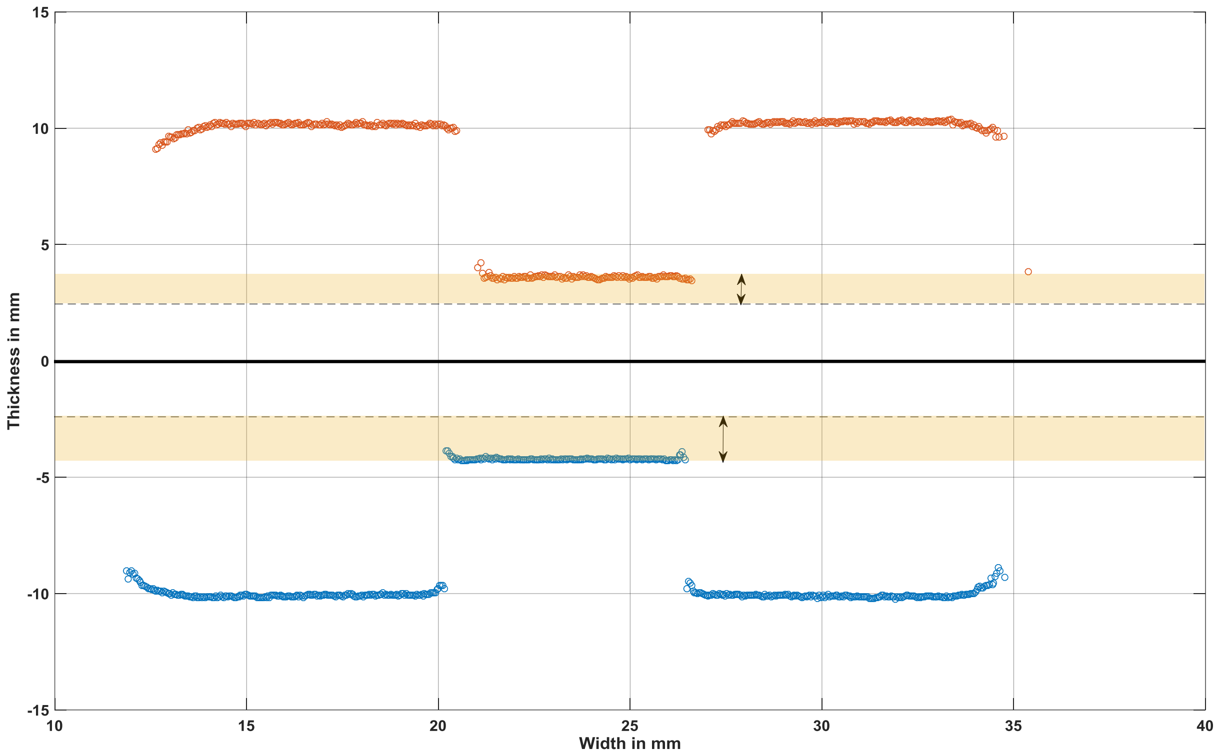

Figure 11. Captured measurement data of the discussed object.

6. Conclusion

This system investigation shows that online differential measurement for evaluating the thickness of elastic material is principal possible. Basically, almost all result adulterating influences are respected in developing a much as is necessary accurate testing measuring system. However, measurement data and estimated uncertainty are not satisfactory. On the basis of this knowledge, the next development steps can be identified. Upcoming researches should deal with possibilities in mechanical adjustments to minimize systematic errors of measurement. Furthermore, a more precise investigation to determine all parameters of uncertainty must be done. Therefore, a separate mechanical design process to ensure stability inside industrial environments must be done as well. Then, the upcoming result of the system investigation will be able to take measurements that are nearly independent by contour, deformation and position inside the scanning area.

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