Measuring Absolute Space Coordinates in Two Dimensions[1]

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Abstract

The paper describes how a two-dimensional absolute measuring system can explicitly be realized. The theoretical background, the experimental setup, the evaluation algorithm, and the results of measurement are discussed in detail.

Keywords: Two-dimensional Absolute Measuring System, Pass Light System, Transformation Measuring System, Two-dimensional Measurement, Micrometre Scale, Decoding of Transformation Traces.

1 Introduction

A tendency in the production engineering goes toward miniaturization. Because of this, it very often is not sufficient to perform a two-dimensional measurement by using two dial gauges for each direction. The measured values are not accurate enough in that case. Nor the values are measured at the same time.
In order to master this problem, direct two-dimensional measuring systems have been developed. However, up to now only incremental measuring systems are available. These systems are not able to continue the measurement immediately after a power failure. Their sensor or standard, respectively, first has to be slipped until a marker is passed over.
A better solution for performing two-dimensional measurements would be represented by an absolute measuring system. Such a system does not need passing over a marker. After switching on, it displays the measured value at each position at once, since the information of the absolute position is encoded in the structure of the standard. The explicit realization of such a two-dimensional absolute measuring system (**xy-system**) is discussed in the following.

[1]This talk was given at the scientific colloquium of the IFMQ of Chemnitz University of Technology on September 19, 2000.

2 Theoretical background

The measuring system under consideration is a so-called 'pass light system', i. e., the standard transmits light.
The system essentially consists of four components; cf. figure 1: a lighting device, a standard, a scanning device, and an evaluation unit.
The functional principle of the measuring system is as follows: Light is emitted from the lighting system and focussed on the standard. Because of the structure of the standard, the light can transmit the standard only at certain domains. A silhouette arises. This silhouette is detected by the sensor line, which explicit is a charge coupled device (CCD), and converted into an electrical signal. Finally, this signal is evaluated. Since there is a bijective relation between the silhouette and the position of the sensor line (or standard respectively), it is possible to calculate the position directly.
The realization of the lighting device is simple. It is sufficient to use a light emitting diode (LED).
The realization of the scanning device is more difficult but nevertheless state of the art. The scanning device consists of a printed circuit board which mainly contains: a clock (quartz), a linear image sensor (CCD line), an analog-digital converter, a field programmable gate array (**FPGA**), and one controller (microprocessor). The scanning device was manufactured by the company TR-Electronic Ltd. [1].
The most elaborated part, however, is the development of the structure of the standard. This work as well as the whole concept of transformation measuring systems has been done by Professor H. Trumpold, Dr. Ch. Troll, and their PhD student at that time, Dr. U. Kipping [2] (see also [3, 4]).
It can be seen from figure 1 that the structure contains three types of traces. The lines which take an angle of $135°$ to the x-axis belong to a datum trace. The lines which take an angle of $90°$ to the x-axis are part of a x-transformation trace. And the lines taking an angle of $0°$ to the x-axis belong to a y-transformation trace.
The sensor line is perpendicular to the datum traces. Thus, the lines of each type of transformation trace cut the sensor line with an angle of $45°$ (or $135°$ respectively). The smaller this angle is, the longer becomes the gauge length. Therefore, the gauge length theoretically becomes infinite for an angle of $0°$. In this way, the boundary caused by the encoding does not play any role anymore. Knowing the structure of the standard, one can calculate the measured values. This calculation is subject of section 4.

3 Experimental setup

Next I would like to present the experimental setup. Figure 2 gives an overview about the essential components. The components are: a flat plate of stone [used

as basis] (1), a linear guide (2), a pneumatic carriage (3), a device (4) for turning at certain angles, a facility (5) for adjusting the standard in two directions, a holding element (6) for the standard (7), a device (8) for adjusting the printed circuit board (9) in three directions, a holding element (10) for the LED, and finally a transformation measuring system (11) which is used for comparing the measured values.
The transformation measuring system [3] is an one-dimensional system. In principle, the measuring system for comparing the measured values must be a two-dimensional one. But such a system was not available.
However, since the cartesian coordinates can be replaced by an angle and a distance in the two-dimensional space one can measure the distance with an one-dimensional measuring system and deduce the cartesian coordinates when the angle is known. This point will be discussed in more detail in section 5.
The standard and the printed circuit board represent the heart of the experimental setup in some sense. They are depicted in more detail in figure 3.
The functionality of the measuring system is outlined in figure 4. The red arrows indicate the directions in which the elements concerned can be moved. In principle it does not matter whether the printed circuit board or the standard is moved. However, moving the printed circuit board can lead to systematic errors since the electrical cables must be carried with. Therefore, I decided to move the standard along the linear guide.

4 Evaluation algorithm

In order to transform the electrical signals into measured vaules, I wrote the following evaluation algorithm. The evaluation algorithm essentially consits of six parts which are discussed successively.

4.1 Communication with the controller

The evaluation algorithm communicates with the controller of the printed circuit board by means of a RS232C interface.
The communication is done in order to get a position array as well as a status arrray from the controller.
The components of the position array contain the positions on the sensor line at which a change of brightness (light-dark, or dark-light) takes place.
Each component of the status array contains the status of the respective change of brightness.
If, for example, the sensor line is partly covered by a plate, compare figure 5, there are two changes of brightness each of them with different status. If the change of brightness is from light to dark, the status is termed with '0', otherwise

with '1'. It is ruled by the signal processing direction of the sensor line whether the transition is from ligth to dark or vice versa.
The communication essentially is done in the following way:

- First, the evaluation algorithm tells the controller to generate new values of both the position array and the status array. The respective command, which is sent from the evaluation unit to the controller, just consists of two integers.
- Then, the evaluation algorithm successively receives pairs of array elements which consist of a position array element and the respective status array element from the controller. For each pair, the evaluation algorithm first sends the array index to the controller and then gets from him both the position and the status of the change of brightness.

When the evaluation algorithm has received all of the position array elements as well as all of the status array elements, he starts with the analysis.

4.2 Calculation of the line widths

First, the line widths are calculated. The i^{th} line width is defined as the difference between the position of brightness change No. $(\mathbf{i} + \mathbf{1})$ and the position of brightness change No. $\mathbf{i}$,

$$\text{width}[i] \quad := \quad \text{fl}[i+1] - \text{fl}[i]\,,$$

where the position array is denoted with 'fl'.

4.3 Finding the datum traces

Then, the datum traces are ascertained. A datum trace consists of six straight lines, compare figure 6. All of the lines have the same width and they are parallel to each other. Further, the distances between the lines are equal.
In order to find out a datum trace, the following has to be done:

- Calculate all of the widths where fl[i+1] belongs to the status 0 and fl[i] to the status 1.
- Compare these widths with an intervall which is chosen with respect to the theoretical width of the datum trace.
- Make sure that none of these widths lies within a certain security domain (cf. figure 6).

The security domain has to be taken into account in order to exclude errors which could arise form the lines of the code blocks of a transformation trace due to the processing process.

4.4 Decoding the transformation traces

Next, the transformation traces are decoded. The code blocks of the transformation traces are numbered consecutively. Because of the number, it is possible to find out whether a code block belongs to the x- or y-direction. Each code block number is encoded by a 12-bit word. It consists of a margin label, a position label, and 24 information labels, see figure 7. An information label can be either a value label or a separation label. The margin label and the information labels have the smallest width. This width is termed unit width in the following. The position label is 4 times the unit width.

In order to decode a transformation trace, first of all one has to calculate the mapping between a detected distance and its theoretical value. The mapping M is defined by,

$$M = \frac{\text{detected distance between 2 datum traces}}{\text{theoretical distance between 2 datum traces}} .$$

In princple there are two ways for decoding a transformation trace.

The first way is: Take a certain label, e.g. the position label. Calculate the distances between this label and each information label. Divide each label by the unit width. If the resulting number is n, set bit $2^{N(n)}$ to 1, otherwise to 0.

The first way, however, has one difficulty. One has to allow a certain tolerance for the practical implementation. Because of this one can get false results if n is large, say $n = 11$.

So, I suggest the following (second) way: Take the position fl[i] as a basis which is between the margin label and the position label. Calculate the differences between nearest neighbour components, i. e., fl[i+n+2] - fl[i+n+1]. Set bit 2^n according to the Nassi-Shneider structure chart which is shown in figure 8.

It can be infered form figure 8 that $4095 = 2^{12} - 1$ if-conditions must be evaluated. Due to the symmetry of the Nassi-Shneider structure chart, however, the implementation of these if-conditionis is simple, see figure 9. It is also seen from that figure that only 7 if-conditions must explicitly be programmed in order to set bit 2^1 until bit 2^{11}.

4.5 Calculation of the actual angle between the sensor line and the datum traces

Knowing the code block numbers, the evaluation algorithm calculates the actual angle between the sensor line and the datum traces. A sketch of the situation is given in figure 10. Due to the adjustment, the actual angle differs from the desired angle of $90°$ by the angle α.

The absolute value of α is computed by

$$\alpha = \arccos \left(\frac{\text{theoretical distance between the centres of two datum traces}}{\text{measured distance between the centres of the datum traces}} \right) .$$

The sign of α is determined as follows: Calculate the length l_x of the detected code block in x-direction as well as the length l_y of the code block in y-direction. Compare the two lengths. If the relation $l_x > l_y$ holds, take the positive sign. If the relation $l_x < l_y$ is valid, take the negative sign.

4.6 Calculation of the space coordinates of the sensor line

Having done the work described in the sections 4.1 until 4.5, finally the space coordinates of the sensor line are computed.
The coherences for calculating the space coordinates of the centre of the sensor line are illustrated in figure 11.
The position P_x of the beginning of the code block in x-direction is calculated by

$$P_x = (29 \cdot [\text{x code word}] - 28) \cdot [\text{unit width}] \,.$$

And the equation for computing the position P_y of the beginning of the code block in y-direction reads,

$$P_y = (29 \cdot [\text{y code word}] - 1) \cdot [\text{unit width}] \,.$$

Then, the x-coordinate M_x and the y-coordinate M_y of the centre of the sensor line are determined by

$$\begin{aligned} M_x &= P_x + b_x &= P_x + c_x \sin\gamma \,, \\ M_y &= P_y + a_y &= P_y + c_y \cos\gamma \end{aligned}$$

with $\gamma = 45° + \alpha$. The distances b_x, a_y, c_x, and c_y are outlined in figure 11. (The angle α is taken from foregoing section.)
Remark: The beginnings of the code blocks undergo statistical fluctuations. In order to minimize the error resulting from these fluctuations, the beginnings of the code blocks are modified by the analysis method 'linear regression' (Gaussian's least square method).

5 Results of measurement

In order to test the two-dimensional absolute measuring system, the following measurements have been performed:

1. Measurement of the space coordinates when the sensor line moves parallel to the datum traces.

2. Measurement of the space coordinates when the sensor line moves parallel to the x-axis.

3. Measurement of the space coordinates when the sensor line moves parallel to the y-axis.

For comparing the measured values, I applied the transformation measuring system (**TMS**) mentioned in section 3. The TMS was manufactured by the company TR-Electronic Ltd. [1].
The following uncertainties of measurement were taken into account in order to calculate the errors of measurement: (The abbreviation 'wrt.' is used for 'with respect to', 'comp.' stands for 'compensation', and 'uncertainty' is abbreviated by 'uncert.' in the following.)

	TMS [μm]	XY-SYSTEM [μm]
– Uncert. wrt. the standard:	± 0.50	± 1.00
– Uncert. wrt. the optical component:	± 0.10	± 1.00
Resolution:	0.06	0.50
– Uncert. wrt. the behaviour of the linear guide:	± 0.03	± 1.00
– Uncert. wrt. the non existent comp. of temperature:	± 0.04	± 0.04
– Uncert. wrt. the violation of Abbe's rule:	± 0.02	± 3.00

The uncertainties of the xy–system refer to both the x-direction and the y-direction.
The results of measurement No. 1. are depicted in figure 12 till 15. It is seen from figure 12, that the x-values as well as the y-values rise linearly. This behaviour is in accordance with the expectation since the sensor line shifts with an angle of 45° with respect of the standard.
In order to get reference values for the actual x- and y-values of the xy-system, the desired x- and y-values have been determined by these two trigonometrical relations,

$$
\begin{aligned}
x_{\mathrm{desired,i}} &= c_{\mathrm{desired,i}} \cos(\phi_{\mathrm{desired}}) \,, \\
y_{\mathrm{desired,i}} &= c_{\mathrm{desired,i}} \sin(\phi_{\mathrm{desired}}) \,.
\end{aligned}
$$

The index **i** indicates the distance between measuring point **i** and measuring point **0**. The hypotenuse values $c_{\mathrm{desired,i}}$ has been measured by the TMS. The angle ϕ_{desired} has been calculated from the slope of the corresponding linear regression line. The uncertainty in calculating ϕ_{desired} was $3.0 \cdot 10^{-3}$ rad.
In order to compare the actual values with the desired values, the following differences have been calculated:

$$
\begin{aligned}
\Delta x_{\mathrm{actual,i}} &:= x_{\mathrm{actual,i}} - x_{\mathrm{desired,i}} \,, \\
\Delta y_{\mathrm{actual,i}} &:= y_{\mathrm{actual,i}} - y_{\mathrm{desired,i}} \,, \\
\Delta c_{\mathrm{actual,i}} &:= c_{\mathrm{actual,i}} - c_{\mathrm{desired,i}} \,,
\end{aligned}
$$

where $c_{\text{actual,i}}$ is computed by $c_{\text{actual,i}} := \sqrt{x^2_{\text{actual,i}} + y^2_{\text{actual,i}}}$. These errors of the actual values are represented in figure 13 until 15. The error bars in these figures have been calculated by using the combined standard deviation. Due to these figures it can be seen that the curves for Δ x, Δ y, and Δ c go up and down over a range of several 10 micrometres. The reason for this behaviour are systematic errors which are mainly caused by a defect FPGA. Because of the defect FPGA, the photo elements of the sensor line (CCD line) were not completely discharged. The result of measurement No. 2. and No. 3. are shown in figure 16 and figure 17 respectively. The curves of figures 16 and 17 are not linear in contrary to the curve of measurement No. 1. This is also due to the defect FPGA. Because of the defect FPGA, the effective length of the sensor line was approximately 8 millimetres shorter than the normal length. Therefore, 3 datum traces partly could not be detected at the same time, as provided, when the sensor line was moved parallel to the x-axis or y-axis respectively.
Despite of the problems caused by the defect FPGA, it can be said that the two-dimensional absolute measuring system, which is described above, is eligible for performing direct two-dimensional measurements in principle.

6 Summary

The aim of this talk was to demonstrate how the two-dimensional absolute measuring system, proposed in [2], can explicitly be realized.
After a brief representation of the theoretical background the experimental setup was explained. Then, the evaluation algorithm was described in detail. Finally, the results of measurement were dicussed.
It turned out that the two-dimensional absolute measuring system is eligible for performing direct two-dimensional measurements in principle. However, due to a field programmable gate array, which did not work properly, the systematic errors, depending on the shift direction, were relatively large.

Acknowledgments

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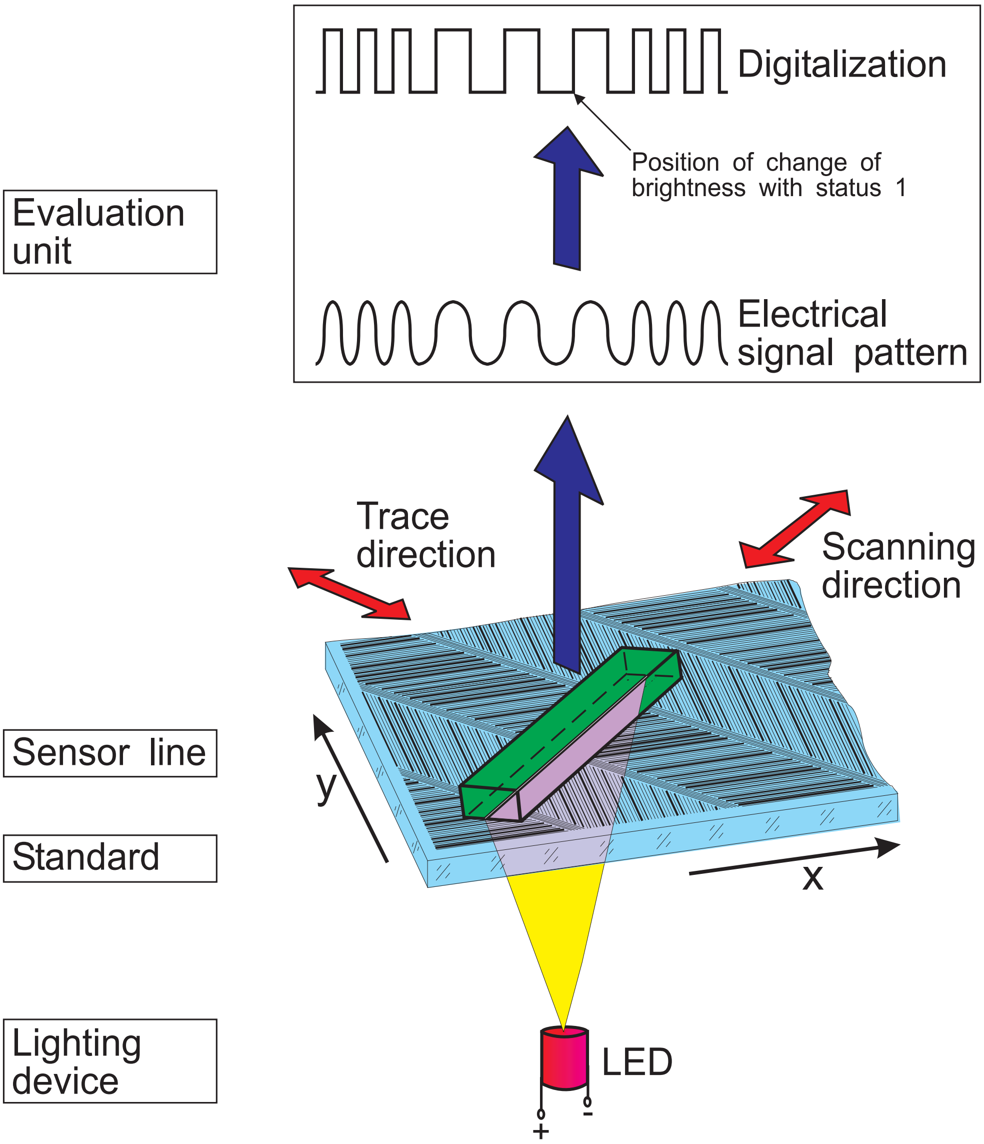

Figure 1: *Representation of generating digital signals.*

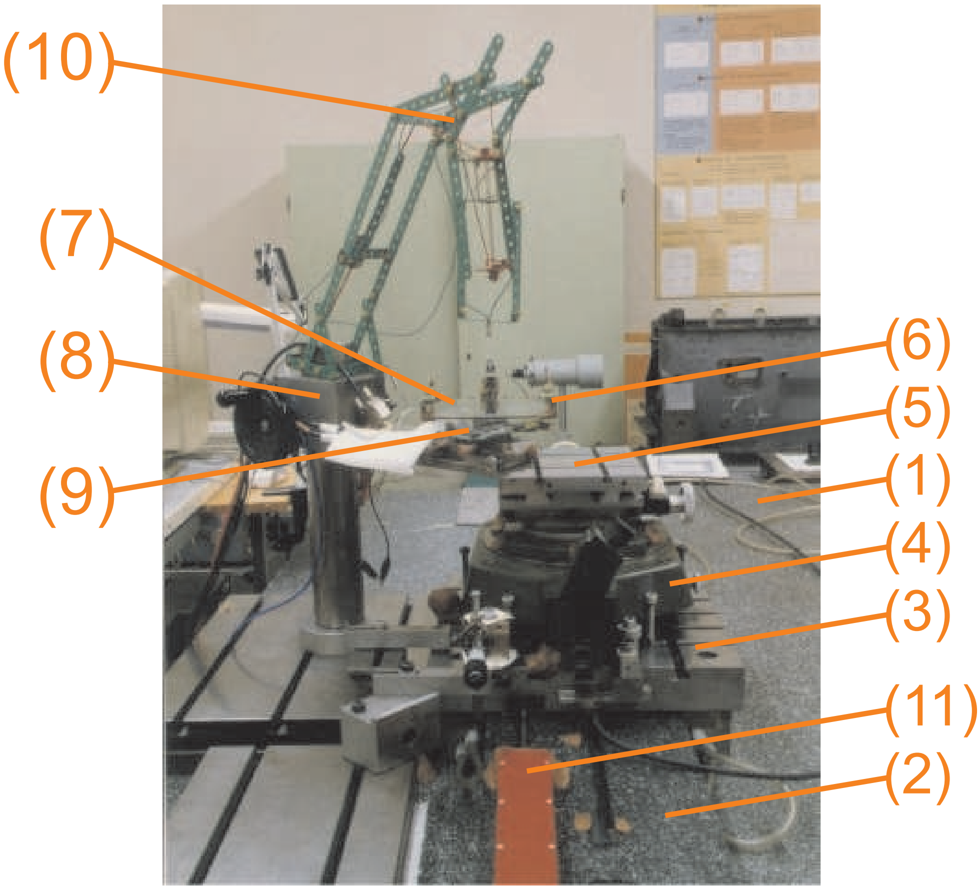

Figure 2: *Experimental setup. Explanation: see text.*

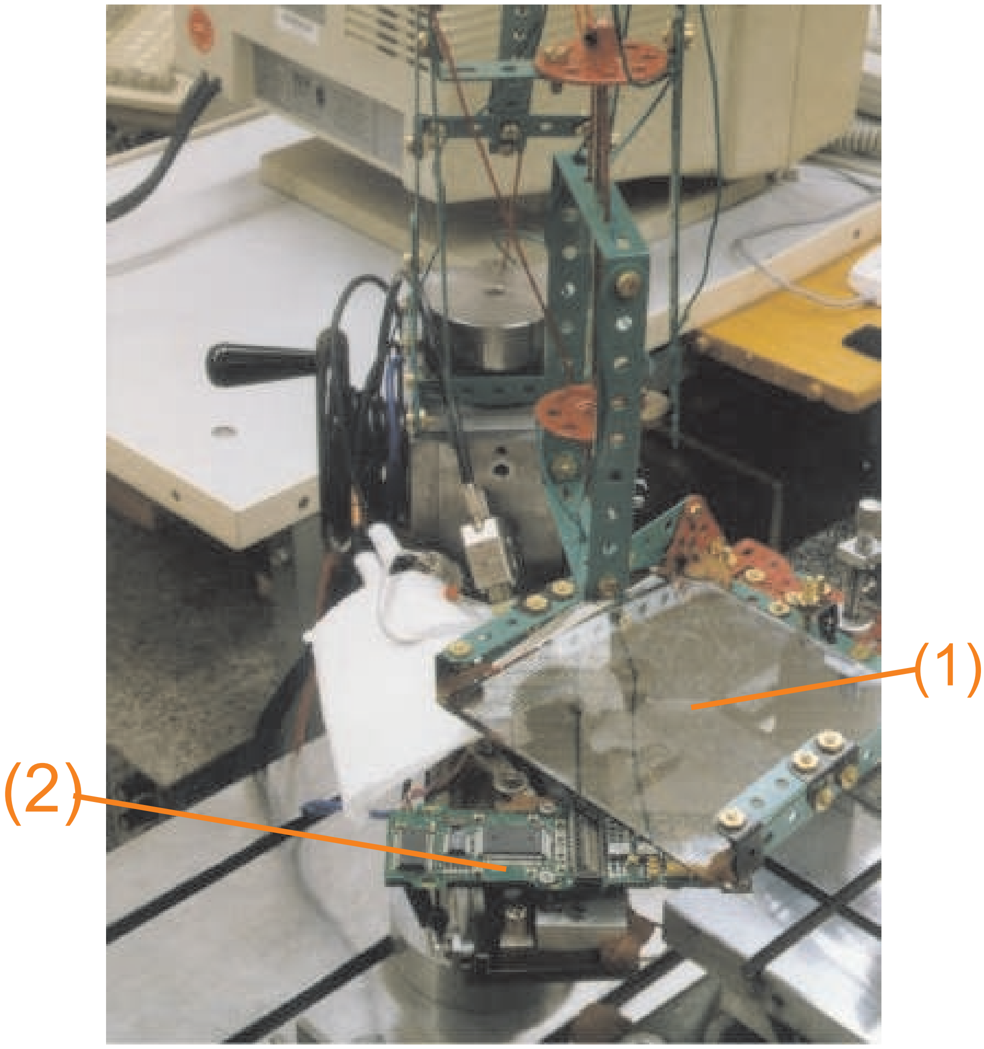

Figure 3: *Representation of the standard (1) and the printed circuit board (2) in more detail.*

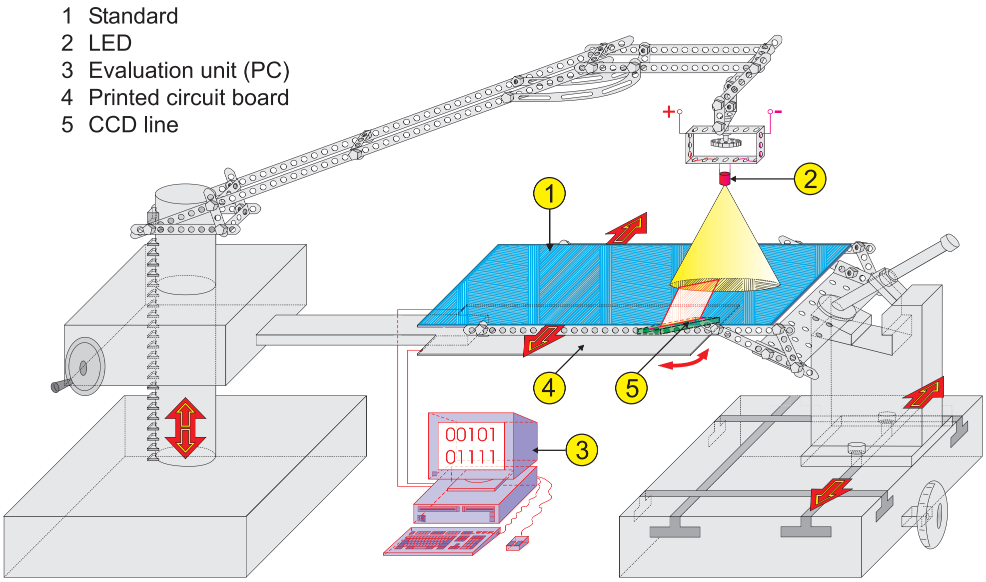

Figure 4: *Sketch of the functionality of the two-dimensional absolute measuring system.*

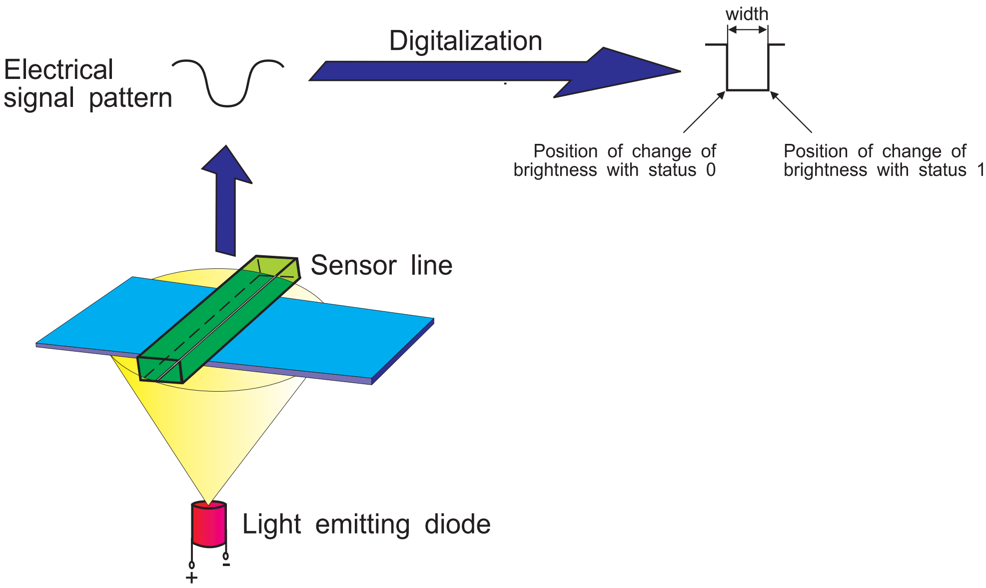

Figure 5: *Sketch of signal processing.*

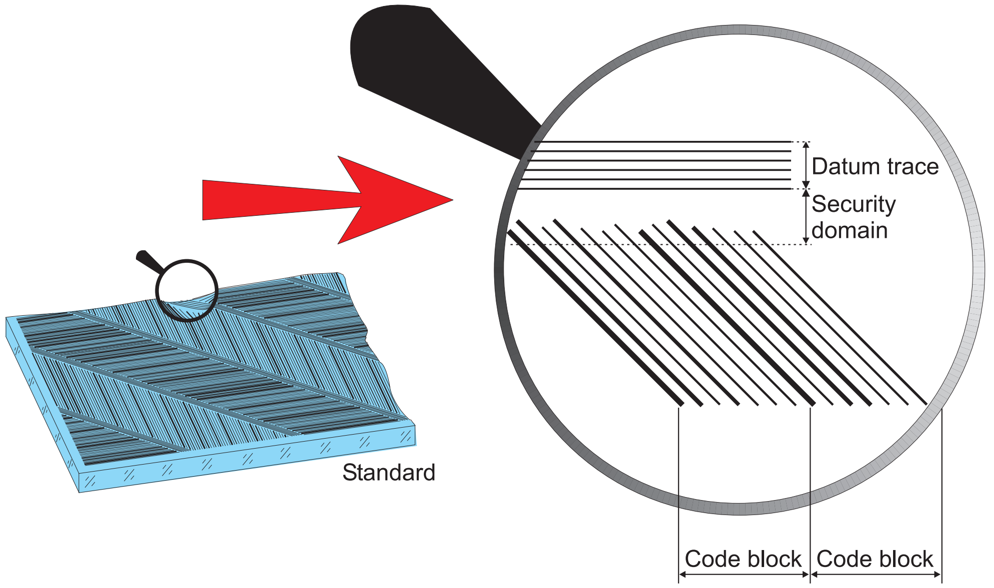

Figure 6: *Sketch of the XY-standard.*

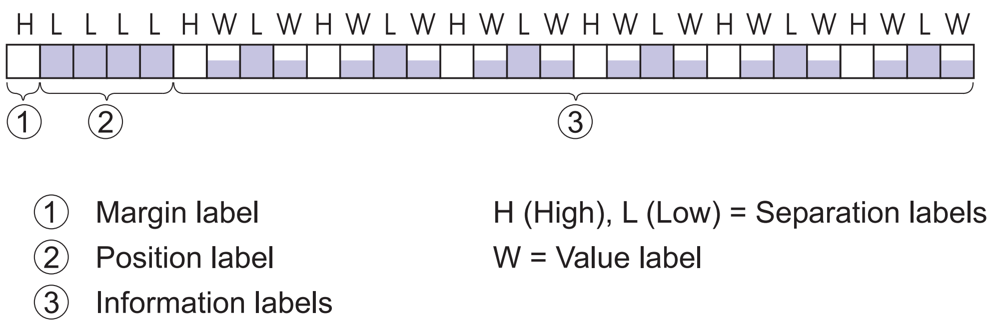

Figure 7: *Graphical representation of a 12-bit word.*

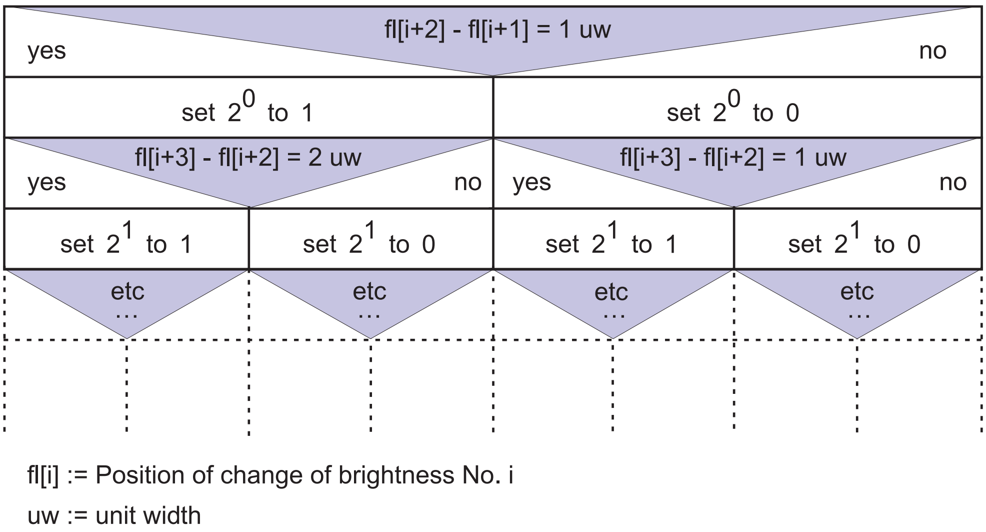

Figure 8: *Nassi-Shneider structure chart.*

```
for x = 2 to 12 do
    if (x even) then
        if (2^(x-2) is set to 1) then
            if (fl[i+1+x] - fl[i+x] = 2 uw) then
                    2^(x-1) is set to 0
            else
                    2^(x-1) is set to 1
        else
            if (fl[i+1+x] - fl[i+x] = 1 uw) then
                    2^(x-1) is set to 0
            else
                    2^(x-1) is set to 1
    else
        if (2^(x-2) is set to 1) then
            if (fl[i+1+x] - fl[i+x] = 1 uw) then
                    2^(x-1) is set to 1
            else
                    2^(x-1) is set to 0
        else
            if (fl[i+1+x] - fl[i+x] = 2 uw) then
                    2^(x-1) is set to 1
            else
                    2^(x-1) is set to 0
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Figure 9: *Numerical conversion of the Nassi-Shneider structure chart into pseudo-code in order to set bit* 2^1 *until bit* 2^{11}.

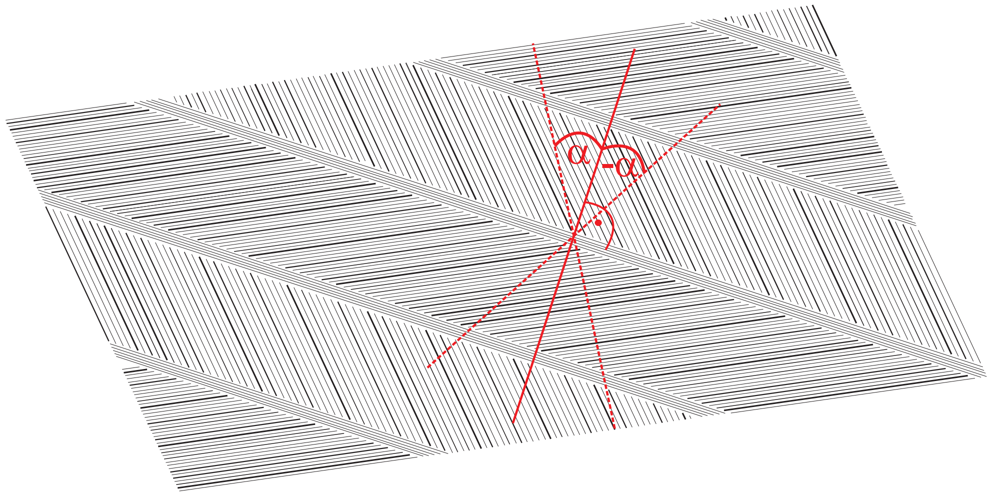

Figure 10: *Sketch of the actual angle of the sensor line. The value of the actual angle is* $90° \pm |\alpha|$.

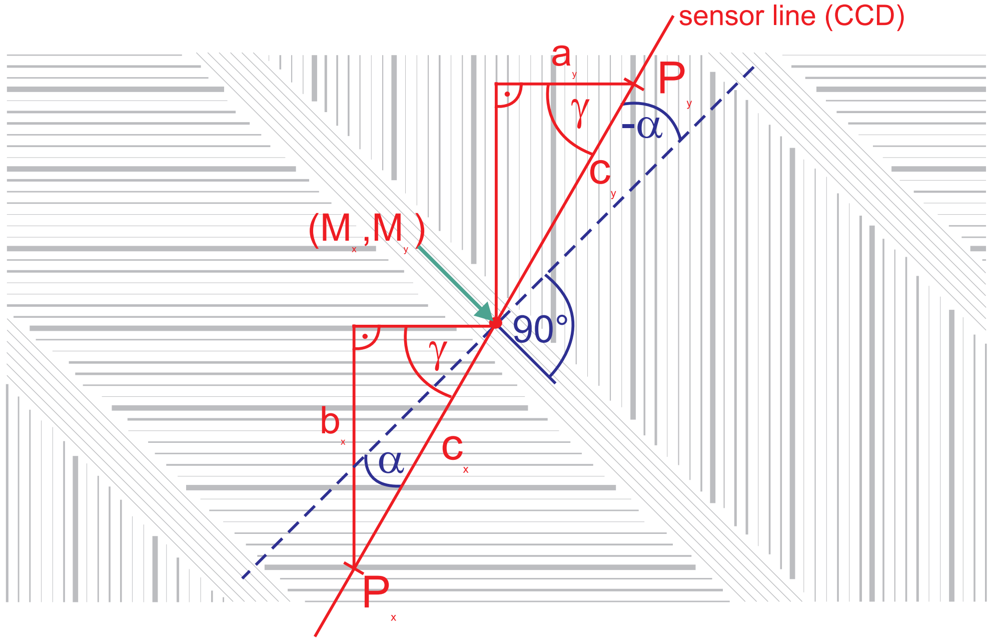

Figure 11: *Coherences for calculating the space coordinates of the centre of the sensor line. The abbrevations are explained in the text.*

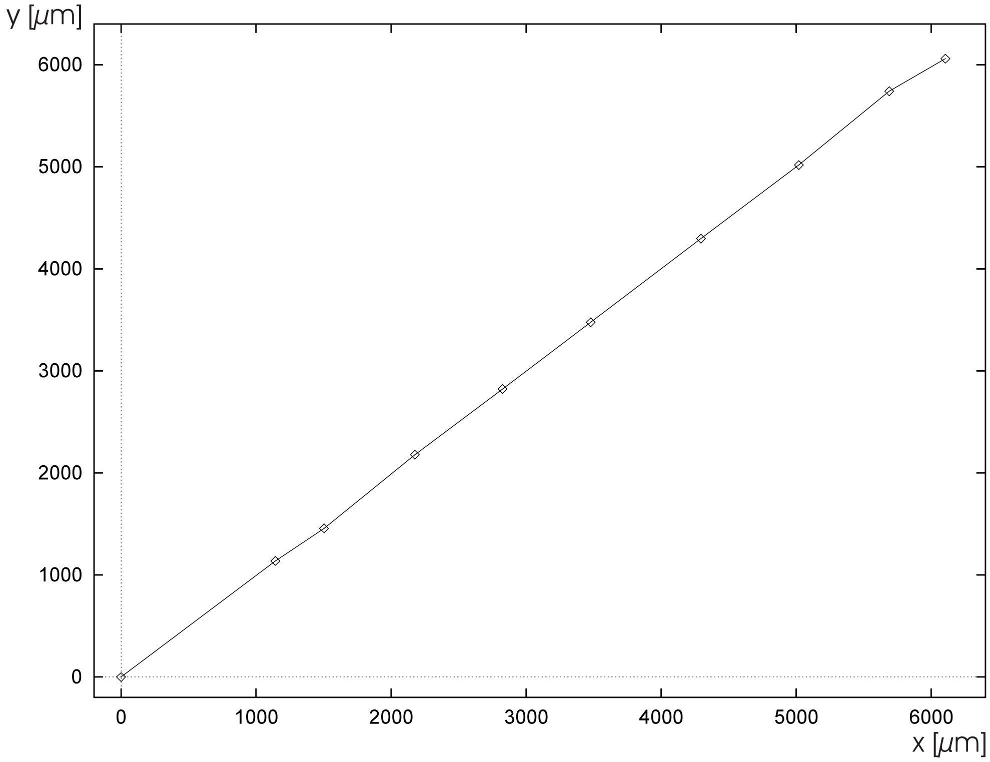

Figure 12: *Actual x-values and y-values when the sensor line moves parallel to the datum traces.*

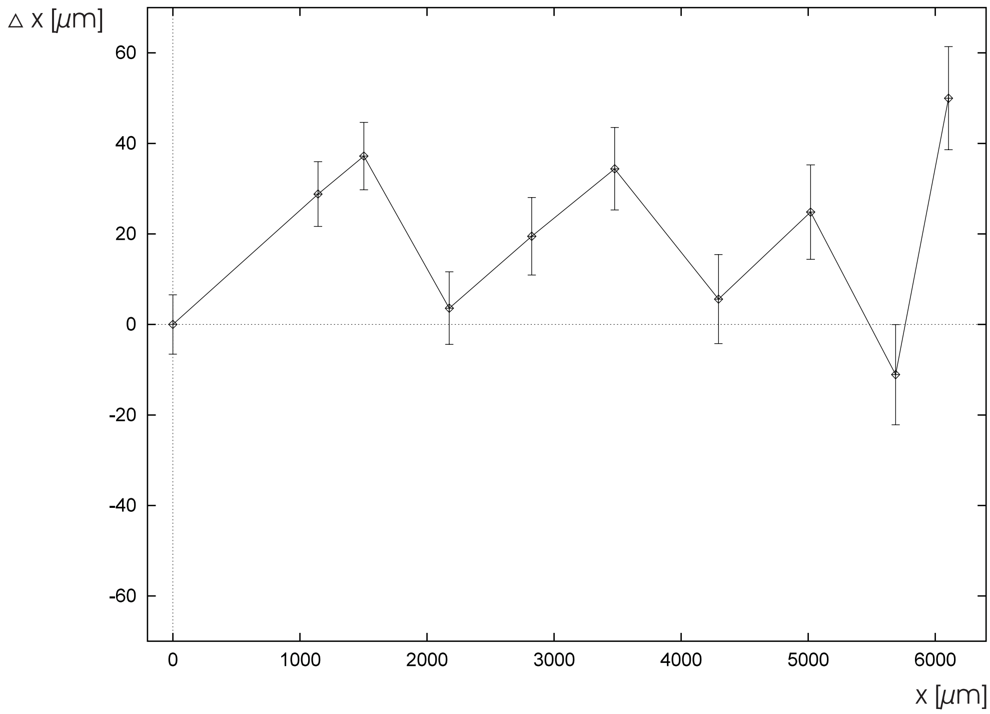

Figure 13: *Error of the x-values Δ x over the x-values.*

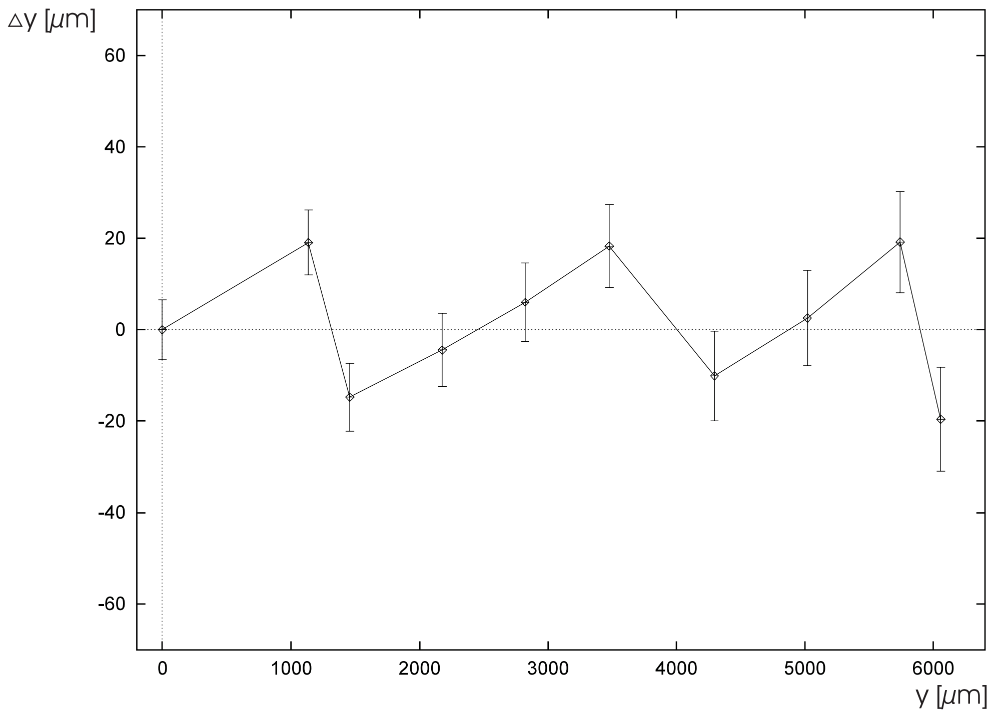

Figure 14: *Error of the y-values Δ y over the y-values.*

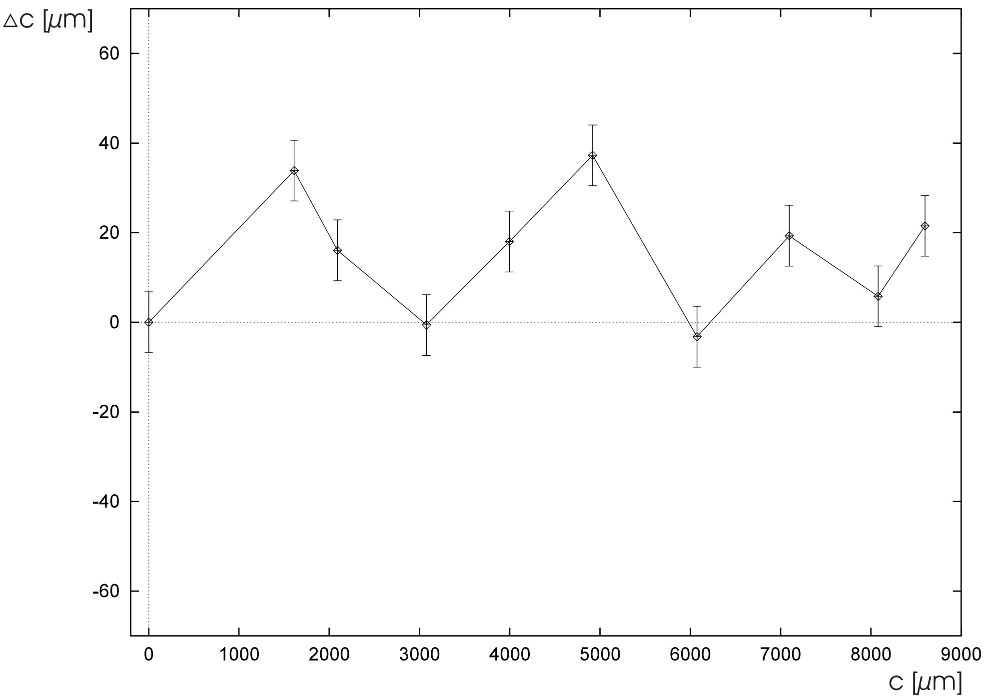

Figure 15: *Error of the c-values* Δ *c over the c-values.*

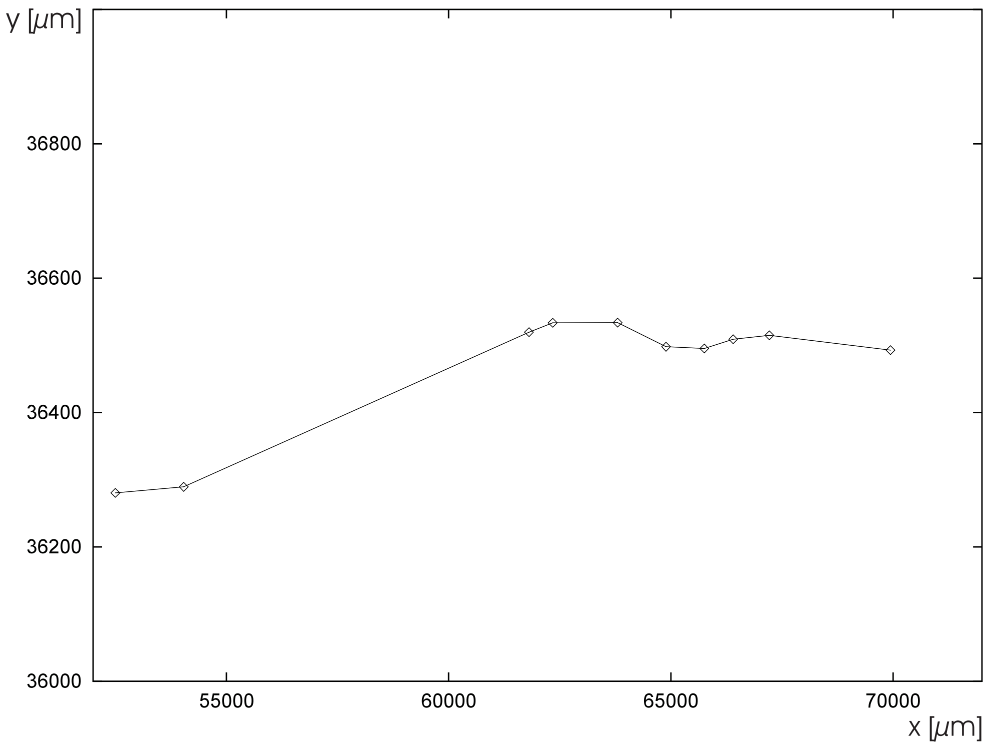

Figure 16: *Actual x-values and y-values when the sensor line moves parallel to the x-axis.*

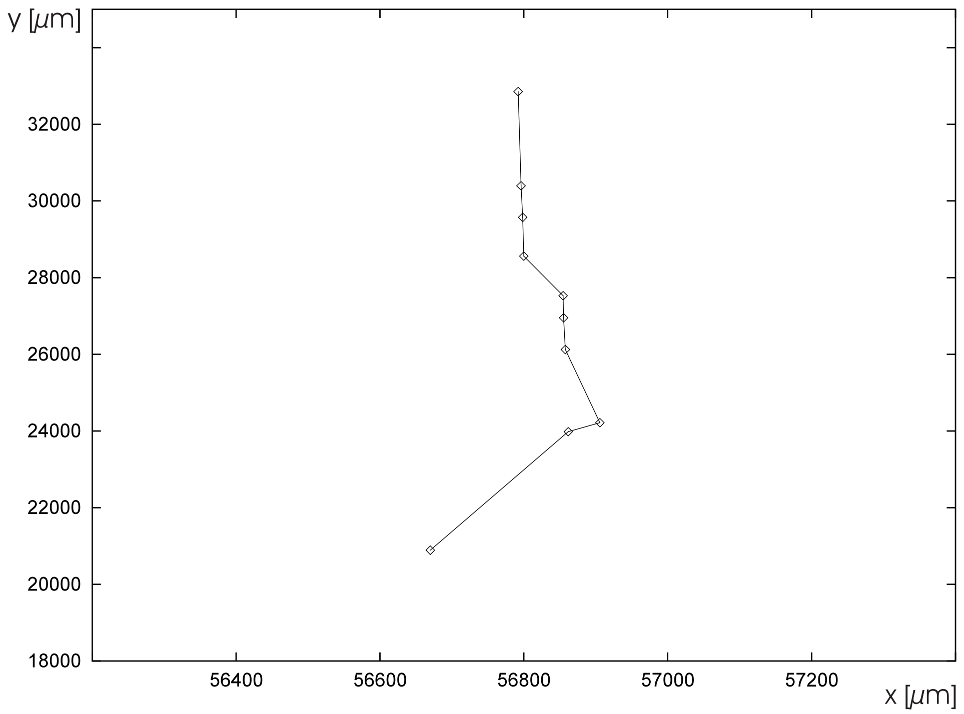

Figure 17: *Actual x-values and y-values when the sensor line moves parallel to the y-axis.*