Surveying and Tuning of a Machine to produce High Precision Components for a Hadron-Electron-Separator

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Abstract

A machine to produce parts for a hadron-electron-separator had to be surveyed and tuned so that it would work with a very high precision. Some adverse conditions and the required high precision made it necessary to develop a special procedure for the survey. Surveying a grid of points distributed over the total area of the machine (for instance by using the forward intersection technique) was not capable of producing the required accuracy. Instead a laser interferometer and a theodolite with a special telescope, suited for autocollimation, were used to give the desired accuracy. This method required the measurement of a relatively small number of angles and distances which resulted in considerable time saving. The procedure significantly improved the precision of the machine and thus avoided the necessity of purchasing and installing more expensive equipment. In this report the chosen method and the results of the survey shall be described.

1 The Machine and Parts to be produced

It was required to install detectors at the HERA Experiment ZEUS, which are able to identify hadrons and electrons within the calorimeter. Parts of these detectors are about 4 meter long and 6 cm wide sheets called skis (see figure 1). Some hundred pieces have to be put on a machine in order to mill holes into the material and glue diodes on the surface. The holes and the diodes should be positioned in X and Y with a very high precision. It was required that the deviation of the actual position from the theoretical one should not be more than +-0.025mm in X and +-0.05mm in Y. The production of the skis is still going on and will take at least 4 years.

The machine was not delivered as a complete device but was assembled at DESY and consists of different components bought from different companies or made at DESY. In fig. 2 one can see a bench , which is 5.5 m long and 80 cm wide. Its surface has been adjusted so that it became flat and horizontal within +- 0.05 mm . On top of the bench were 2 slides (see fig. 3a and 3b). Each of them could be moved by means of one driving spindle. Slide A was movable in the X-direction and slide B which was situated on top of slide A could be moved in the Y-direction. The movements were displayed on a terminal as X- and Y-coordinates.

2 The Requirement to the Surveyors

It was our task to check how accurately the machine was working by comparing the displayed coordinates with coordinates derived from surveying . The detected differences between these two coordinates should be introduced into the control mechanism of the machine to improve its precision.

3 The Measurements

3.1 Measurements from stand 1 to the bench

a) We put a theodolite on stand 1 which was situated on the straight line 11-12 , which was parallel to the edge of one rail (see fig. 3b). With the special telescope of the theodolite it is possible to carry out conventional angle measurements and in addition angle measurements via autocollimation. It is suitable as an alignment telescope because its line of sight is almost straight and its collimation error is almost zero. In front of the theodolite, on the same straight line 11-12 , we installed a laser interferometer. At slide B was mounted a target (C) for angle measurements , a mirror for the autocollimation , and a reflector for the distance measurement with the laser interferometer.

b) The slides were moved to the position where the display showed X=Y=0. We measured the angle α between the target C and the straight line 11-12 and the autocollimation angle β (see fig. 4). In addition the laser interferometer was set to zero. Then the slide A was moved to the displayed position X = 20 cm , slide B remained in Position Y = 0. The same angle measurements as before were carried out and the distance from X = 0 to X = 20 was measured by the laser interferometer. The same procedure was repeated along the straight line Y = 0 for X = 40 cm , X = 60 cm , X = 80 cm . . . . . . X = 440 cm.

c) We expected that the machine would be affected with a hysteresis depending on the direction in which the slide moved. Therefore we moved the slide some cm beyond X = 440 and than backward to X = 440 , X = 420 , X = 400 . . . . . X = 0 and made the same measurements as described in section b).

d) The result of the measurements was the following (see fig. 4) :

For each surveyed position of slide A one could calculate the value ΔYCi by means of the angle α and the distance of the target from stand 1. The angle β between the surface of the autocolhmation mirror and the Y-axis is equal to the measured autocollimation angle β. The X-coordinate XCi is given by the laser interferometer.

If the machine was affected by hysteresis ; the angles β measured when slide A was moving forward would deviate from the angles β which were measured by moving the slide backward. For each surveyed position of the slide the deviation would be equal to a systematic amount $\Delta\beta$ as in fig. 5. Such a systematic amount was recognizable. It was equal to 0.0015 grad +- 0.0004 grad respectively 0.013 mm +-0.003 mm over the width of the bench . This is a very small hysteresis. However at one position of the slide a bigger $\Delta\beta$ occured , caused by an out of flatness of the rail.

In the distance measurement with the laser interferometer no hysteresis between moving the slide foreward and backward was recognizable . However the distance measurement showed that the length of the bench was influenced by the temperature of the air which changed during the day , so that the airconditioning had to be improved.

3.2 Determination of the Axis 2-5-6 and Preparations for the Measurements from Stand 2

On stand 1 the angle φ between axis 1-11-12 and point 2 was measured (see fig. 3b). This was done very carefully in several sets of angle measurement in order to reach a high precision. The theodolite was put on stand 2. The axis 2-5-6 should be perpendicular to axis l-11-12. Therefore one could calculate angle ψ by subtracting angle φ from 100 grad.

The autocollimation mirror and the reflector for the laser interferometer were turned by 100 grad so that they were visible from stand 2 and 4.

3.3 Measurements on Stand 2 and 4

Slide A was moved forward to position X = 220 cm , where it remained during the following measurements. Slide B was moved to position Y = 0 . On stand 2 were measured the angle ε between the target and the axis 2-6 and the autocollimation angle ϑ (see fig. 6). The laser interferometer on stand 4 was set to zero. Distance D1 was measured by measuring tape.

Slide B was moved to position Y = 10 cm and the above angle measurements were carried out again. In addition the distance $\Delta Yi+1$ from Y = 0 to Y = 10 cm was measured with the laser interferometer. D2 was calculated by adding D1 and $\Delta Yi+1$. The same procedure was repeated when slide B was moved to position Y = 20 cm , Y = 30 . . . . . Y = 60 cm.

The measurements on stand 2 and 4 were done again by moving slide B in intervals of 10cm from y = 60 cm to Y = 0. In order to take into account the hysteresis of slide A we moved slide A at first a little bit forward and then backward to position X = 220 cm and repeated the measurements on stand 2 and 4 as described in this section.

3.4 Measurements on Stand 7

We put the laser interferometer on Stand 7 , moved slide A to position X = 0 and slide B to position Y = 60 cm and set the laser interferometer to zero (see fig. 3b). Then we moved slide A to X = 20 cm , X = 40 . . . . . X = 440 cm and measured the distance to each position of the slide A. Angle measurements were not done for these position of the slides.

4 The Calculations

4.1 Angle between Track of Slide B and Y-Axis

All ΔYCi were calculated as described in section 3.1d. The angles ε, measured on stand 2 (see fig. 6) and the distances D1 , D2 . . . . were used to calculate the ΔXi. The ΔYi were measured by the laser interferometer.

The ΔXi were the displacements perpendicular to 5-6 (see fig. 7). ΔYi were the displacements from C parallel to 5-6. The axis 5-6 was parallel to the Y-axis of the machine. Therefore ΔXi and ΔYi formed a local coordinate system for the traverse C-D. A least squares adjustment (fit) was made to the data to determine the straight line G. The angle γ between line G and axis 5-6 was calculated.

4.2 Angle between Autocollimation Mirror and Track of Slide B

The autocollimation mirror which was attached to slide B should be mounted so that its surface is parallel to slide A and respectively parallel or perpendicular to the axes on which the slides moved. However a small deviation is unavoidable due to the limits of mechanical machining and mounting of the mirror support.

Now it was possible to calculate this deviation by means of angle γ and the autocollimation angle β measured on stand 1 at the corresponding position of the slides X = 220cm, Y = 0 (see section 3.1 b-c). This deviation (in fig.7 corresponding to angle λ) is
$\lambda = \gamma + \beta$. In our case $\gamma = 0.0222$ grad , $\beta = 0.0093$ grad and $\lambda = 0.0315$ grad.

By chance the straight line from C to D was parallel to the straight line G so that angle λ was also valid for the line from C to D.

4.3 Analysis of Measurements

From stand 1 and 3 we carried out measurements when slide B was at position Y = 0 and slide A moved in 22 steps (each 20 cm wide) along the X-axis at Y = 0 . That means that one has data for 23 positions of slide A.

From stand 2 and 4 the measurements were related to an unchanged position of slide A (it remained on X = 220) and the slide B which moved in 6 steps (each 10 cm wide) along the Y-axis at X = 220cm. The result were data for 7 positions of slide B.

These few data , which were surveyed in relatively short time , could be combined by means of angle λ and the autocollimation angles β and used to calculate the coordinates of 7 x 23 = 161 positions of the slides , distributed over the total area of the machine like a grid .

In fig. 8 the ΔXi and ΔYi (from fig. 7) were inscribed. They were used to calculate the angles p and the distances S for the traverse from point C to D. The angles ρ could be checked. One has to derive the azimuth of each side of the traverse from these angles ρ and compare the azimuths with the autocollimation angles measured on stand 2. In order not to expand the report too much this procedure will not be explained in detail.

If slide B was moving from C to D it followed the traverse. This traverse was the track of slide B and its geometrical shape was valid for every position of slide A , independent of the X-coordinate of slide A. However , the position of the total traverse relative to the coordinate axes from one position of slide A to an other changed.

In fig. 7 the starting-point C of the traverse has an offset ΔYC from the X-axis which was calculated according to section 3.1d . In the same section the calculation of the coordinate XC was explained. The azimuth ω of the straight line from C to D has to be calculated according to the following formula (see fig. 7) :

$$\omega = 300grad - \beta + \lambda \tag{1}$$

ΔYC , XC and ω were the values, which changed from one position of slide A to another , while the shape of the traverse remained unchanged.

For the complete calculation (161 points) the following was included for the traverse at position X = 220 cm of slide A (see fig. 8 and 9):

a) The X- and Y-coordinate of point C which were equal to XCi+m and $\Delta YCi+m$.

b) Angle ω as an azimuth.

c) The angles ρ and the distances S of the traverse.

Similarly the input for all the other positions of slide A was included. In fig. 9 an example for the position X = 600 cm is presented.

$\Delta YCi+n$ and XCi+n were calculated according to section 3.1d.

In order to get the azimuth ω for the straight line C-D one has to introduce the autocollimation angle β (see fig. 4) which was measured at this position of slide A and angle λ (fig. 7) into the equation (1) according to figure 9.

4.4 The Complete Least Squares Adjustment

In order to improve the accuracy and to check for errors within the measurements we measured the distances with the laser interferometer on stand 7 (see section 3.4). These additional distances were introduced into the complete least square adjustment (fit) for all 161 points.

As approximate coordinates for each of the 161 calculated points , the nominal coordinates which were displayed by the machine , were put into the fit. Within the fit the following transformation was carried out : the system of actual coordinates was shifted in X and Y and rotated within the plane which was formed by the X- and Y-axis until the sum of the squares of the deviations between the two types of coordinates was minimized.

5 Result of the Survey and the Calculations

5.1 Detected Inaccuracy of the Machine and Tuning the Machine

As a result of the fit we have actual coordinates and deviations between the theoretical and the actual coordinates. The biggest deviation was 0.3 mm in X and 0.13 mm in Y. The deviations were introduced as corrections in the system which guided the machine.

In order to cancel the hysteresis during the production of skis the machine was programmed so that the slides moved only forward.

5.2 Remarks about the Accuracy of the Survey

The distances measured on stand 7 were redundant measurements. These distances have to match with the distances measured on stand 3 and the azimuths of the straight lines C-D which were correlated with the autocollimation angles measured on stand 1 . The residuals for all distances measured from stand 3 and 7 within the fit did not exceed 0.01 mm . The residuals of the corresponding azimuths were smaller than 0.0010 grad.

The ΔYCi according to fig. 4 were not checked therefore their accuracy was not improved within the fit by means of redundant measurements. It would have been possible to get redundant measurements by measuring the angles α on stand 7 in the same way as it was done on stand 1. But there was an easier and time saving way to get the same effect :

As fore mentioned the detected deviations between machine-coordinates and calculated coordinates were introduced as corrections in the system which guided the machine. Some metal sheets were placed parallel to each other on the machine . The machine milled holes into the sheets. These holes were equidistant and should follow straight lines which were parallel to the X-axis (see fig. 10). Then the sheet number 2 was rotated by 200 grad according to the arc in the drawing and put onto sheet number 1. Sheet 2 was adjusted with respect to sheet 1 by means of two dowelpins which were put into two drilled holes. If the milled holes would have an offset ‘d’ from the straight line one would recognize at each pair of holes twice the amount of ‘d’ as a deviation from one hole to the other. In the same way were compared sheet 3 with sheet 1 and sheet 3 with sheet 2 . All the deviations detected during this procedure in Y-direction were within the required accuracy of +-0.05 mm.

In order to check whether the machine was working accurately enough with reference to the X-coordinates we did the following : After the corrections were introduced into the machine distances were measured with the laser interferometer along 3 lines which were parallel to the X-axis. The slide A was moved as before in intervals of 20 cm. The deviations were as follows: between neighbouring situated points smaller than 0.02 mm , (in one case 0.04 mm) , over the total length of the bench between 0.04 and 0.065 mm.

6 Reasons for using this Method

An often used and for myself a preferred method is the measurement of forward intersections. However in our special case it would have several disadvantages.

a) The shape of the room where the bench was installed and the lack of space would lead to foreward intersections which were far away from ideal geometric conditions.

b) In order to avoid additional mistakes affected by the machine it was necessary to install the target and mirrors as low as possible close to the surface of the bench. However in this position they could be aimed at only from the frontside. If the theodolite would be situated at the rearside of the machine the lines of sight to the target would be covered by the slides. This fact also would lead to disadvantageous forward intersections and to a lack of redundant angle measurements which were absolutely necessary in order to improve the accuracy.

The choosed method however enables us

a) to use the high precision of the laser interferometer and of the autocollimation.

b) to recognize hysteresis or temperature influences during the measurement and not after a time consuming measurement of forward intersections and calculations and to take measures immediately in order to reduce those effects.

c) to determine a lot of points distributed over the total area of the bench by surveying only a few angles and distances along two or three axes.

Acknowledgements

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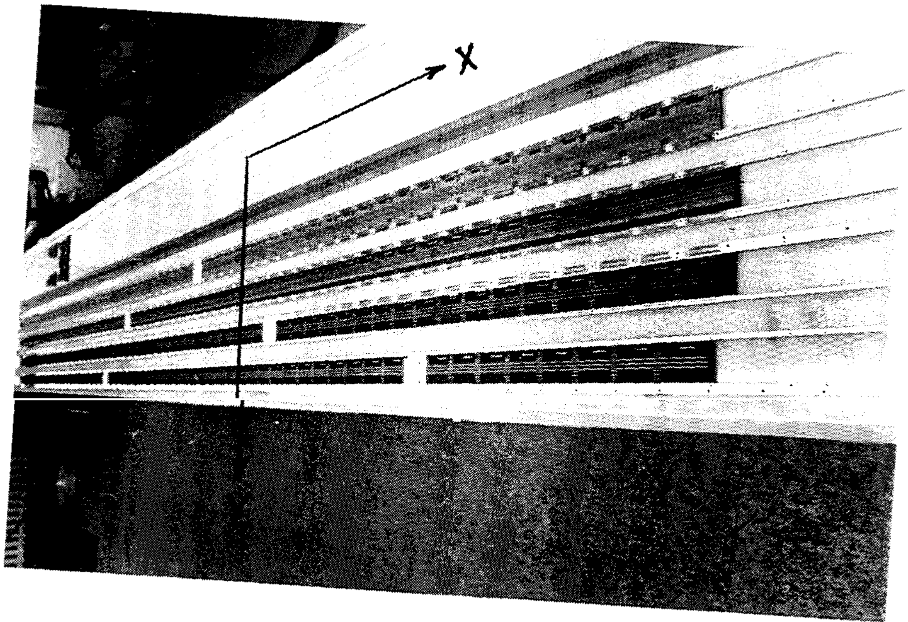

Fig. 1

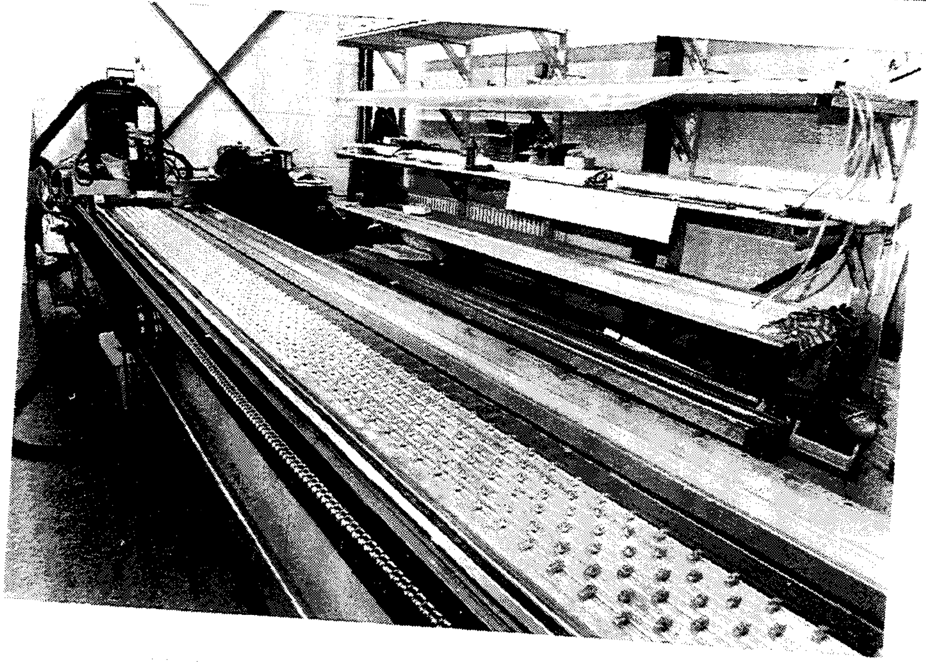

Fig. 2

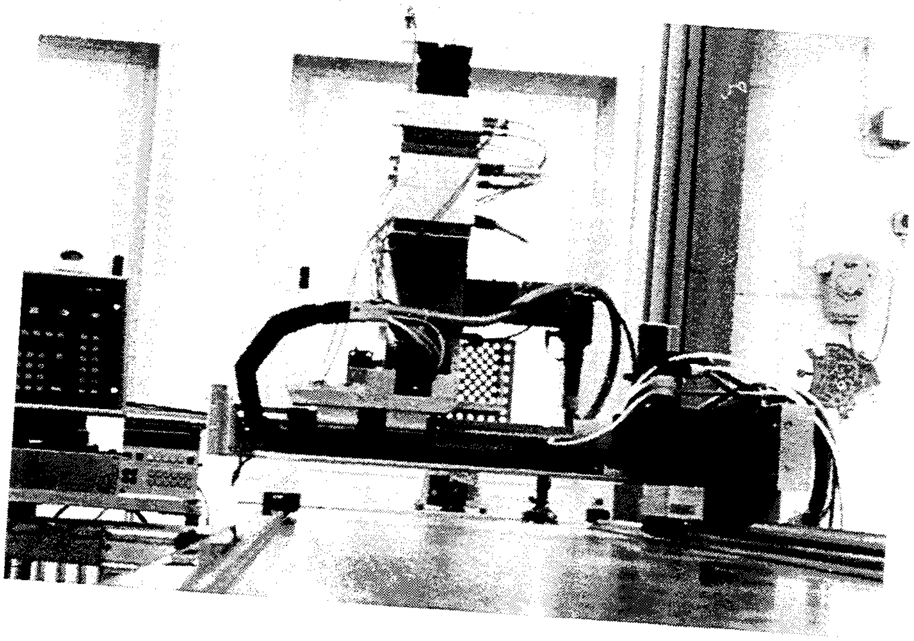

Fig. 3

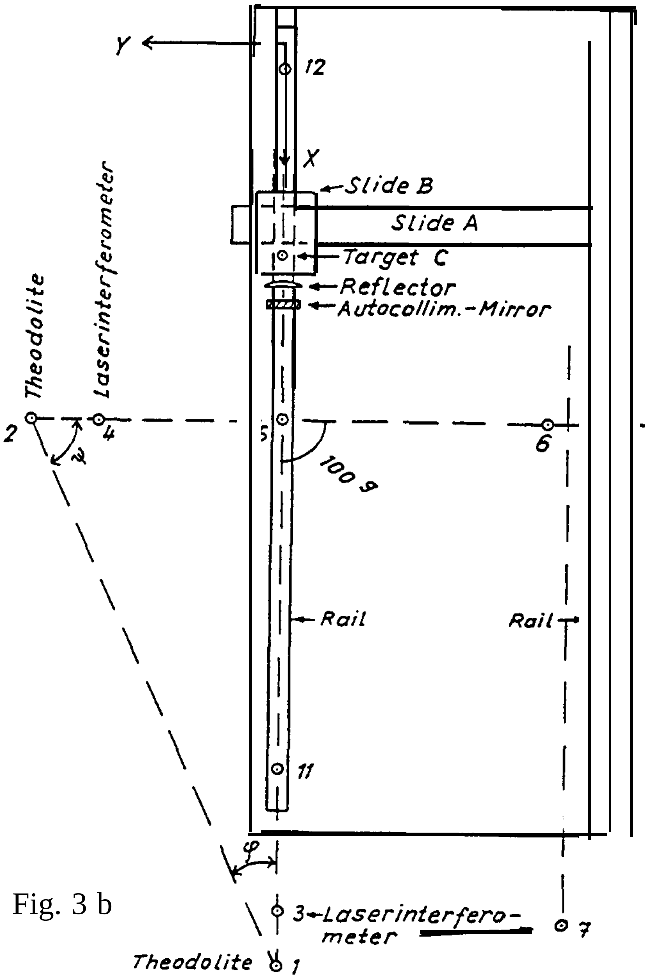

Fig. 3 b

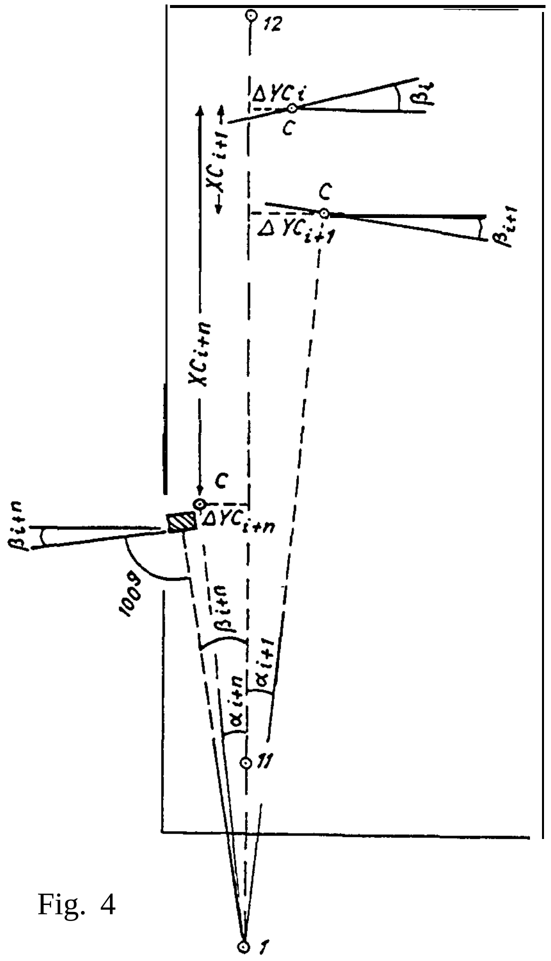

Fig. 4

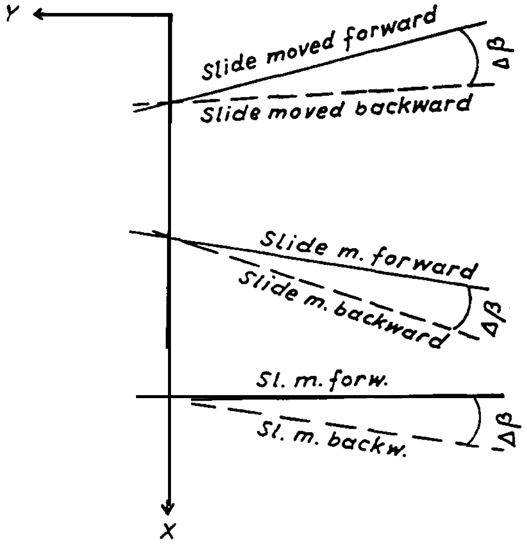

Fig. 5

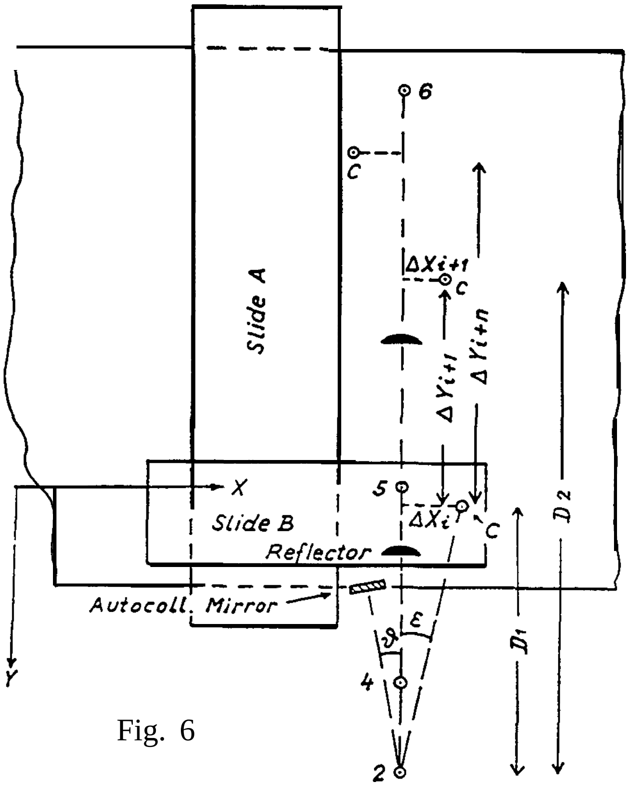

Fig. 6

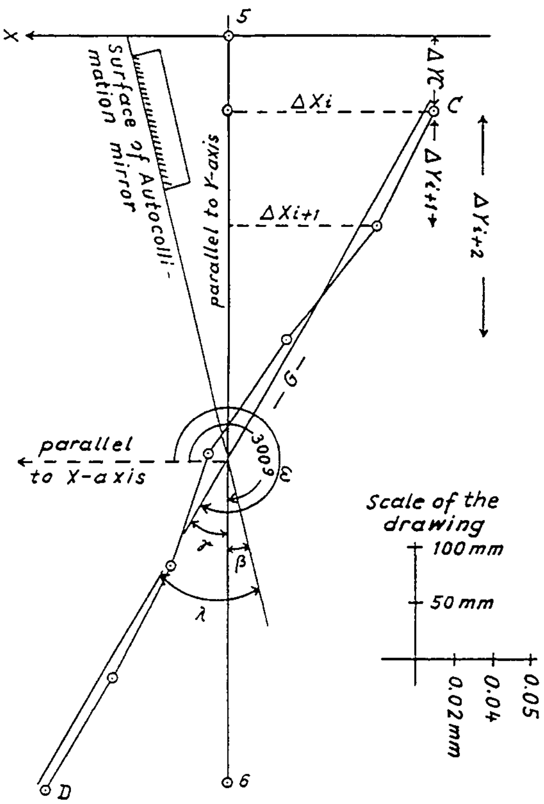

Fig. 7

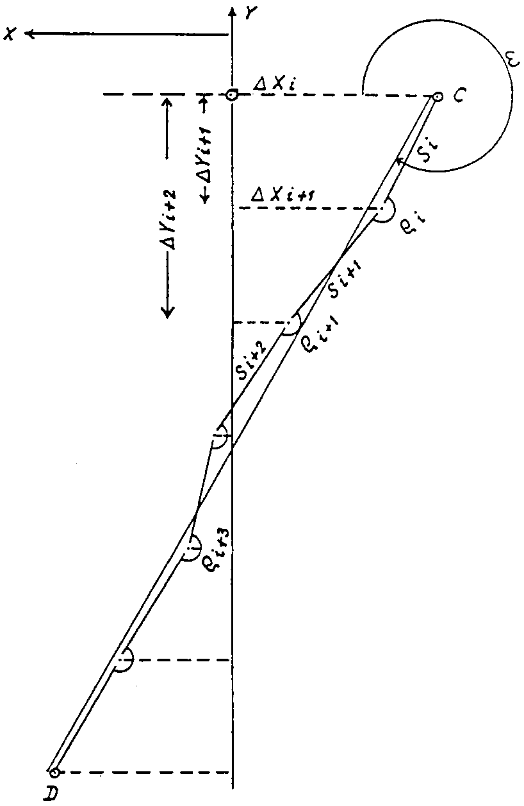

Fig. 8

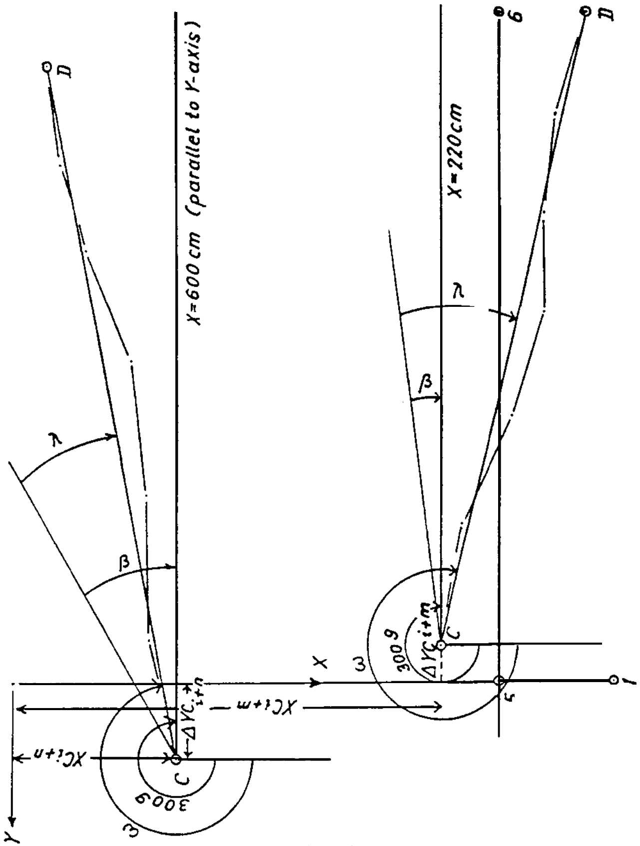

Fig. 9

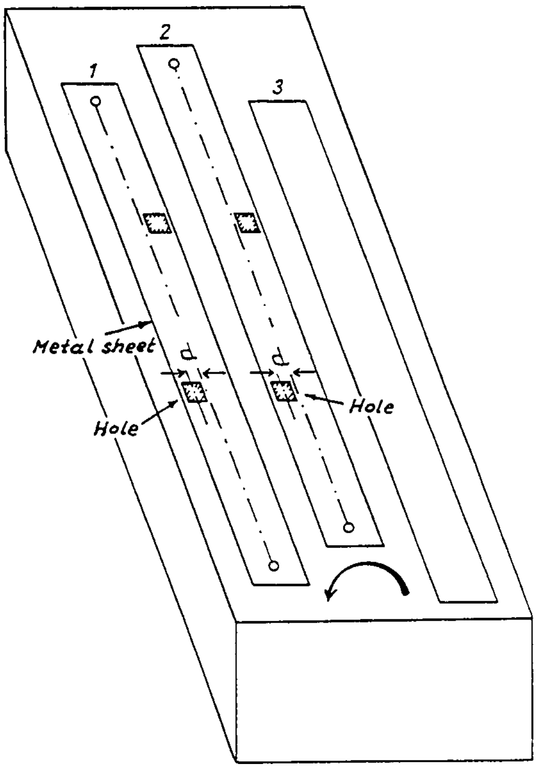

Fig. 10