Image Processing Automatic Interferometric Calibration System for Line Scales

Gonzalez H. * [a], Galvan C. ** [a] & Muñoz J. A. [b]
[a] Centro Nacional de Metrologia, Apdo. Postal 1-100 Centro, C.P. 76000, Querétaro, QRO., México.
[b] Centro de Investigación en Matemáticas A.C., Apdo. Postal 402 Centro, C.P. 36000, Guanajuato, GTO., México.

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ABSTRACT.

An automatic calibration bench to calibrate line scales up to three meters has been developed at the Centro Nacional de Metrología in Mexico. It incorporates an heterodyne laser interferometer to follow the position of a carriage that supports a microscope with a CCD camera. The images are processed using a novel robust algorithm to determine the center of each line. The carriage travels along guide ways and is commanded by a computer that controls the servomotor that moves it, allowing to complete the calibration automatically.

The measurement and control software developed uses an image processing algorithm based on Gabor filters and robust statistics to discriminate between lines and unwanted features that may exist such as stain, scratches, rust, etc. It then calculates the absolute position of each line by coupling the reading of the carriage position given by the interferometer and the centerline position of the line in the image. Additionally, the software corrects the laser readings for ambient condition variations and controls the progress of the carriage.

The mechanical design consists of a stiff bench with guide ways on which the carriage travels. Although the carriage travels in non-kinematic guide ways, the microscope and CCD camera sit on a plate that is kinematically supported. The movement is provided by a servomotor and transmitted by means of a screw.

Uncertainty is expected to be between 3 and 10 µm which is common to other similar systems. The major advantage is the capability to calibrate automatically and discriminate defects on the scale.

I. INTRODUCTION.

In dimensional metrology there are several calibrations that require either expertise or time, for instance the calibration of gauge blocks by comparison require both, nevertheless this process is completely and successfully automated for several laboratories.

The calibration of line scales offered for laboratories and industry in Mexico, they are not good enough, and calibrations carried out by our staff in CENAM consume time of specialized operators and equipment, which is not intended for this purpose, for instance, the calibration of one three meters line scale just in twenty-two lines consumes, in average, at least two days, and involves the use of a CMM with a CCD camera. Besides the fact that the demand for calibrations of this kind of line scales is almost continuous all over the year. Another disadvantage associated to these calibrations is the uncertainty, in some cases even equal to or greater than the encountered deviations.

* hgonzale@cenam.mx ** cgalvan@cenam.mx

All of this caused that the Dimensional Metrology Division decided to develop a system to satisfy the following requirements:

1. Totally automated in the measurement, just needs the scale and the instrument setup .
2. Possibility to select among different groups of lines to calibrate.
3. Maximum scale length up to 3 m.
4. Avoid confusion with lines of rust, damage and scratches on the scale.
5. Improvement of the uncertainty of current calibration process.

II. DESCRIPTION OF THE DEVELOPED SYSTEM.

We have studied different kinds of instruments used in line scale calibration, and the most of them are based on an optical illuminated microscope. In most of these systems the light from the source illuminates the scale. The reflected light intensity is measured by an optoelectronic sensor, the optimal solution if the line scale is in excellent conditions, but the line scales that has to be calibrated has in some cases poorly conditions.

Therefore, when one system that employ a light reflection is used, the signal obtained has a high signal to noise ratio, and the detections of borders of line is quite difficult. For these reasons we decided to develop a detection system based on an image processing approach with higher repeatability.

The developed system is showed in figure 1:

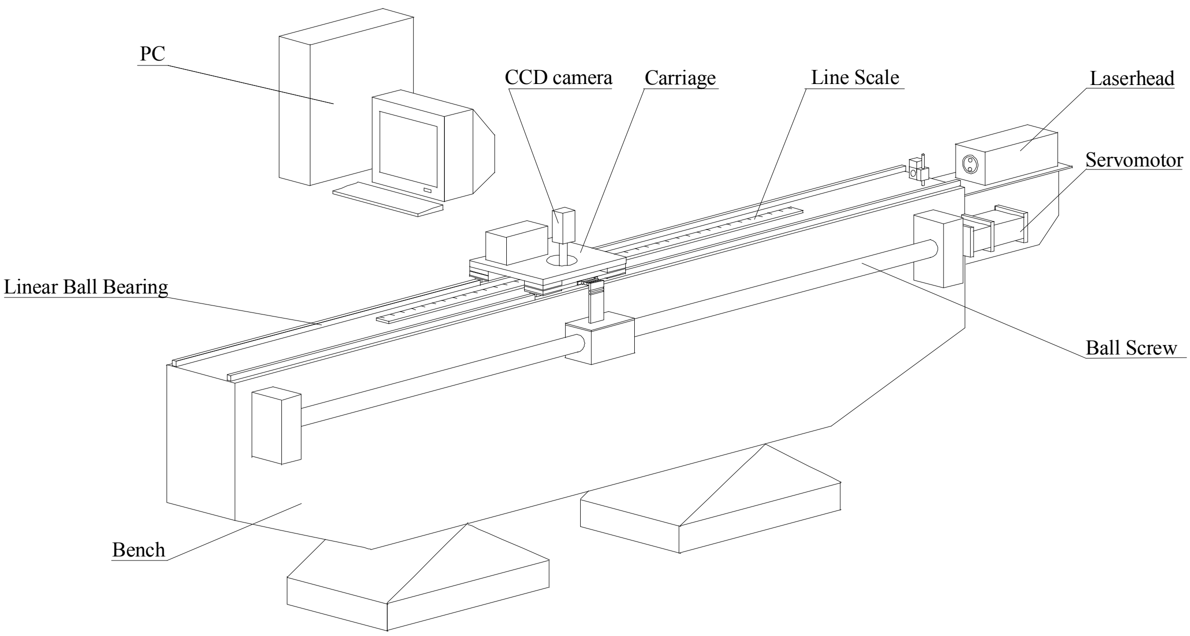


Fig. 1. The Image Processing Automatic Interferometric Calibration System for Line Scales

III. THE MECHANICAL SYSTEM.

The main parts are those shown in figure 1.

The bench was designed with high stiffness, in order to minimize the deflections caused by the movement of carriage. It carries the microscope, the CCD camera, and the light source. The rectangular section of the bench, made of steel, gives the desired stiffness without being too heavy. The top of the bench was machined and the flatness obtained is about 35 μm. On the top of this bench were installed two linear ball guides upon which the carriage travels along.

The carriage moves upon two linear ball guides, and as each one has two small carriages, there are four supports. Therefore, when the carriage is fixed on those supports, the straightness deviations and thermal distortions could affect the repeatability of the system, taking into account that the movement may be restrained or not along the rails in some cases. In order to reduce this disadvantage, it was needed a kinematic support. The chosen configuration is in figure 2.

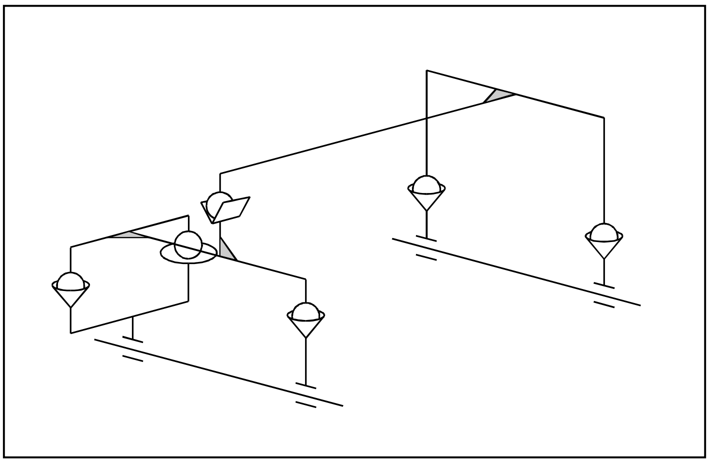


Fig. 2. Connection of carriage with the bench.

This configuration successfully reduces the contributions of mechanical distortions and thermal effects and the carriage smoothly moves along all the way with a good repeatability, even under different temperature conditions.

The supports were made using a ball of hardened steel and machined cones of M2 steel hardened to 60 HRC, rail and flat both with similar characteristics, in one side of the carriage there are two cones these just has the freedom to move along the rail, the other side has either one cone in one carriage and one cone and plane in the other, that avoid rotation and gives stability, both sides are connected by means of one ball on one rail, then the effect due lack of parallelism of rails is reduced.

The carriage moves along the bench by means of one ball screw, which is commanded by a servomotor with gear reduction. However the ball screw is not exactly parallel to the rails on the bench, even more there is a natural deflection on the ball screw caused by its own weight. Then we needed to transmit the movement of the ball nut to the carriage just in one direction, in order to reduce the distortions of the ball screw itself and the lack of parallelism. This was achieved using a flexure system. The flexure stiffness is high enough in the direction of movement and provide an accurate movement to carriage, but in perpendicular directions to the movement the flexure system can be deformed and is capable to reduce the transmission of distortions to the carriage.

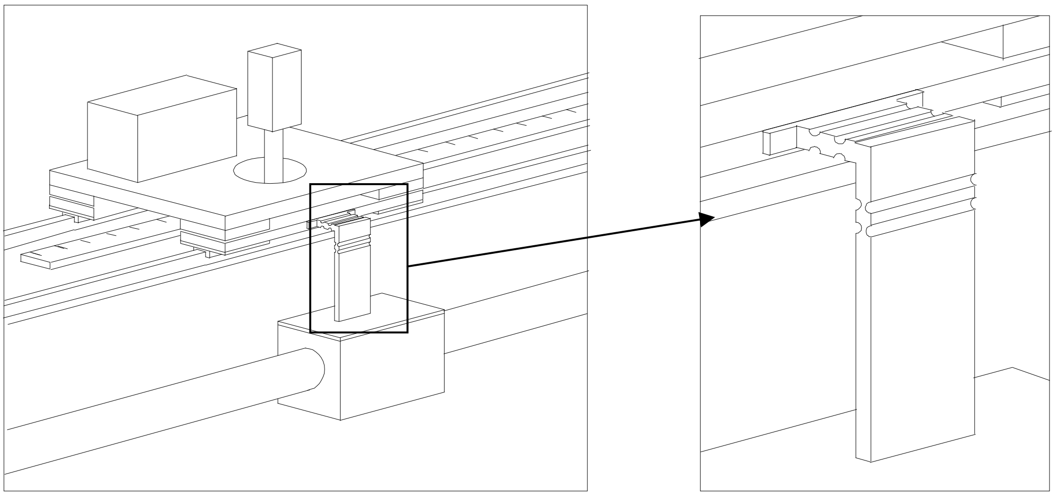


Fig. 3. Flexure transmission from the ball screw to the carriage.

The autocollimation technique was used in the evaluation of the straightness in the movement of the carriage. Here are the results:

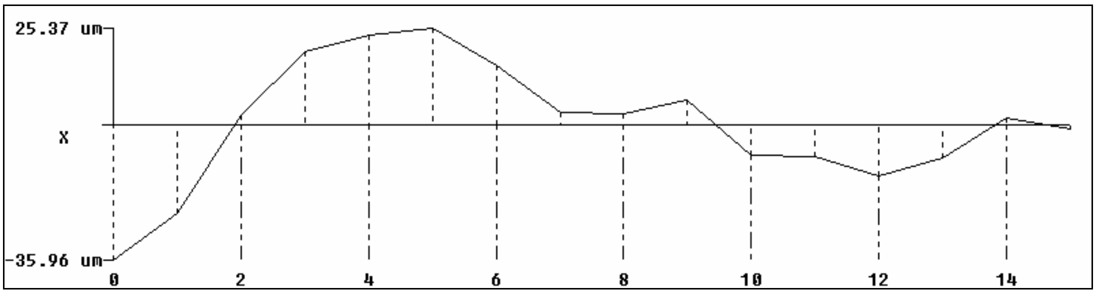


Fig. 4. Pitch deviations of carriage along linear ball guides.

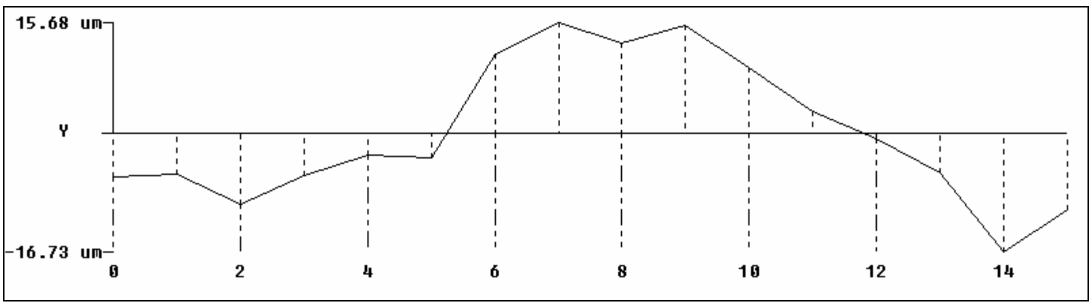


Fig. 5. Yaw deviations of carriage along linear ball guides.

V. TOTAL SYSTEM STRUCTURE

Figure 6 shows the block system diagram for the total system. The system is fully controlled by a PC; commands for the traveling table. The position accuracy in this system is not a critical variable due robust method to calculate center of the graduated lines as is explained in next section.

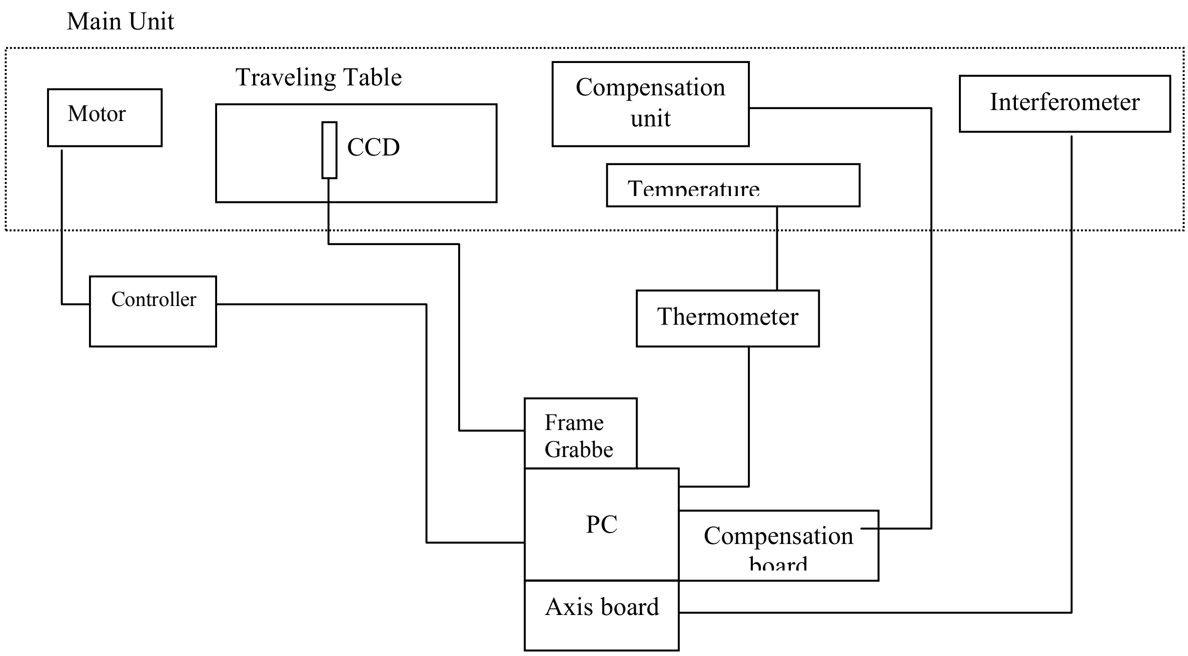


Fig. 6. System block diagram.

VI. SOFTWARE DESCRIPTION

As mentioned before when line scales are calibrated, it is essential to accurately detect the position of the scale lines. In this job is used a novel method that works off-line to measure the distance between the graduated lines. This process consists of determining with high accuracy the distance between graduated lines. For this purpose we used a vision system (VS) that consists of one microscope and a CCD camera (shown in figure 1), the position of the VS with respect to the origin in the line scale is determined by the laser interferometer. The VS is displaced over the scale, storing the captured images and recovering the position from the interferometer (Z). The distance Z corresponds to the position of the VS when the image was captured related to the initial position.

Software system is designed in two phases: first one, obtains all data from system that means: images from VS, position from laser interferometer, temperature from PRT's placed on bench close to scale and temperature and pressure from environment trough a compensation unit. Those values are captured for each line on the scale previously determined by the user, and for each line are obtained four position along CCD image, motion is provide by a servomotor controlled by the computer system.

Next stage is made off-line, the line calibration process is concentrated in two parts: First is to determine in a robust way the equation of the line which is better fit to the center of the line contain in the image. To detect the center of the line in each column with a sub-pixel precision, the algorithm uses a Gabor complex filter which is a well known quadrature filter this process is done for every row in the image. The Gabor filter is designed in space domain and is defined by equation 1

$$h(x) = g(x)\left[\cos(\varpi_0 x) + j\sin(\varpi_0 x)\right] \quad (1)$$

where: $g(x)$ is a gaussian function with $\sigma = \varpi_0/4$ and half frequency period ϖ_0 is similar to the width for line in pixels in the digital image. This filter is applied for every row in the digital image. After that, algorithm looks for a maximum on the modulus in the filtered signal, and with a neighborhood given in pixels (around 5 for example), select phase values and find the mean line, the point where this lines cross zero, this is taken like center for the line in this row.

Continuing with line detection process is necessary to fit a line with points of line obtained for each row in the digital image, as mentioned in last paragraph. For this part the algorithm uses a robust linear regression approach, in order to eliminate outliers in the data due defects in the scale line, image grabber, illumination effects etc; which can introduce a bad estimation for the line. The algorithm uses a M-estimator which general approach is shown in equation 2 for a line

$$U(m,b,a) = \sum_{i=1}^{n} \rho\left(\frac{y_i - mx_i - b}{\alpha}\right) \quad (2)$$

where α is a scale parameter. ρ function indicates error modulus, in this case we choose a truncated quadratic functions as ρ, the equation 3 shows

$$\rho(x) = \begin{cases} x^2 & |x| < a \\ k & \text{other wise} \end{cases} \quad (3)$$

Minimizing function U the algorithm obtains the line parameters for the line, after that the algorithm eliminates points (outliers) that are located out of a region determinate by the user, and recalculates line parameters, this process iterates until algorithm reach a confidence range.

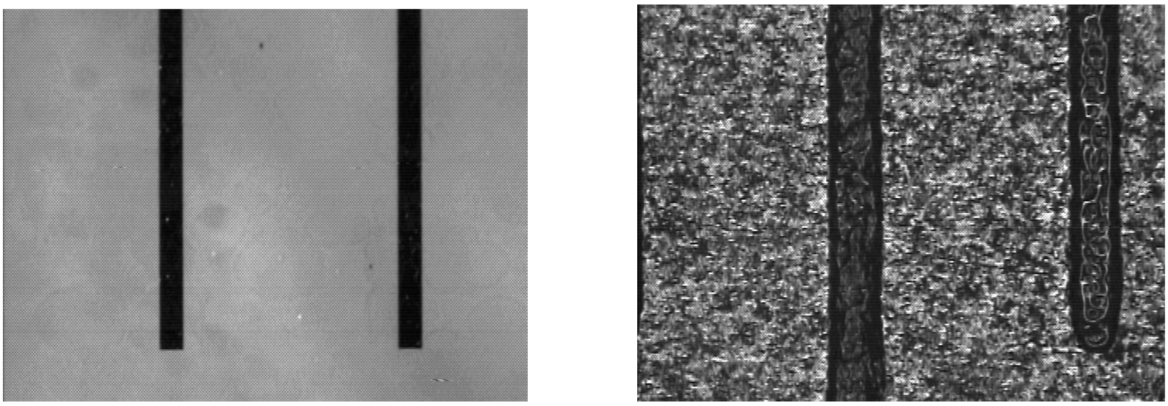
With lines detected, is necessary give them a location with the reference, for this process we use the relation shown in equation 3

$$z^w = z_i + \beta x_j \quad (4)$$

where z^w shows real position for line j, and β is scale factor for each pixel in CCD. This process takes interferometer readings and position for a same line along calibration process (in practical cases, the first line is taken in different images along CCD interval, in order to determine this factor), this number is calculated solving equation system shown in equation 5

$$z_0 + \beta x_0 = z_1 + \beta x_1 = \cdots = z_n + \beta x_n = z^w \quad (5)$$

With the factor and the sensor coordinate, the center of the mark is mapped to global coordinates obtaining the distance for all graduated lines. The proposed method offers too more information about the physical state of the rule, for example the slope of the lines between them etc.



Glass scale | Steel scale

Fig. 7. Images captured from different kind of linear scales.

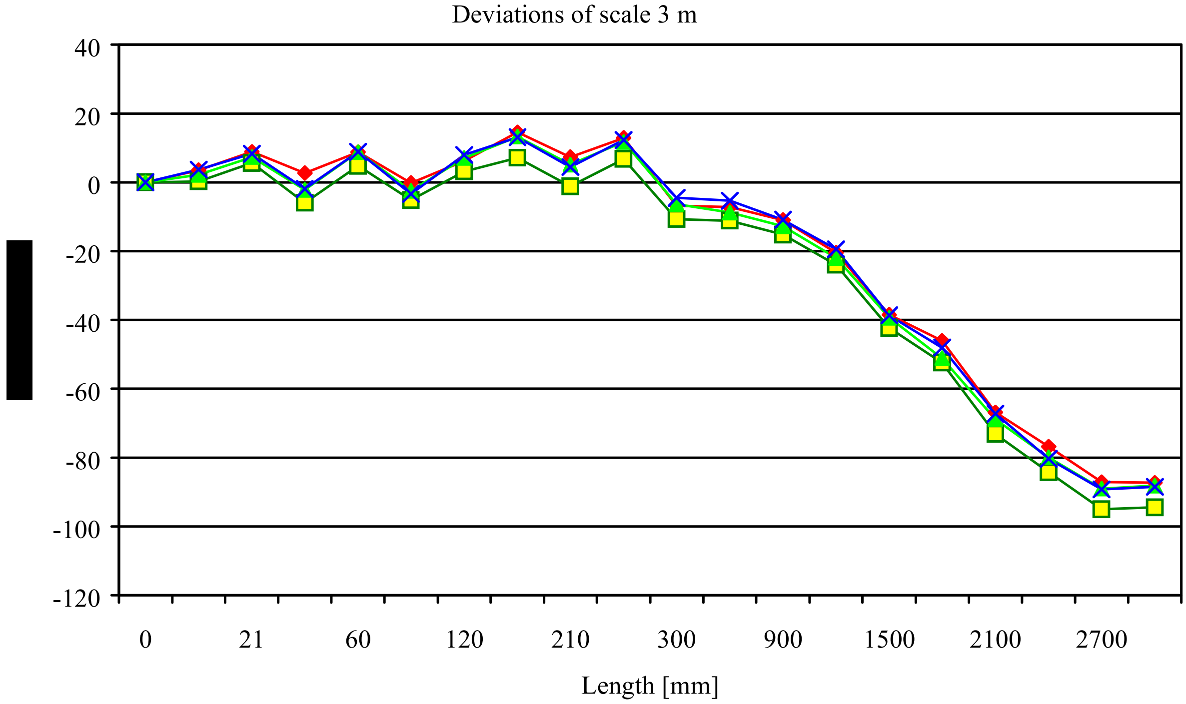


Fig. 8. Deviations of 3 m scale

Figure 8 shows a measurement example for a steel scale up 3000mm, this figure contains three different measurements to show system repeatability. In this case measurements were not done in equidistant lines. This scales produce in the Vision System digital images like shown in figure 7, where line edges are not well defined, this situation justify to use a robust method to detect centers for graduation lines.

VII. MEASUREMENT UNCERTAINTY

The measurement uncertainty was evaluated under the guidelines of the well know Guide to the Expression of Uncertainty in Measurement. The model was:

$$d = l_r\left[1-\alpha\cdot(t_r-20^{o}C)\right]-\left\{\left[\frac{m\lambda}{n}-\frac{l_{dp}}{n_i}+\frac{l_{dp}}{n_f}\right]+l_p\cdot f\right\}\left(1-\frac{\theta^2}{2}\right)-l_a\cdot\beta+l_d\cdot\frac{\tau^2}{2} \tag{6}$$

in order to determining the combined standard uncertainty of equation 6, we evaluate conform the model:

$$u_c^2(y)=\sum_{i=1}^{n}\left[\frac{\partial f}{\partial x_i}\right]^2 u^2\left(x_i\right) \tag{7}$$

The results obtained for the values in table 1 was a expanded uncertainty of 9,51 μm, with a coverage factor k=2.

Source of uncertainty		Input quantities		Value of standard uncertainty
Length of the scale	**lr**	3000 mm	**lr**	0 mm
Thermal expansion coefficient	**α**	1.1 μm/100 mm ºC	**α**	0.11 μm/100 mm ºC
Scale temperature	**tr**	21 ºC	**tr**	0.100005 ºC
Fringes number	**m**	4738513.055	**m**	0.001
Length of wavelength	**λ**	633.11 nm	**λ**	0.00005 nm
Refractive index of air	**n**	1.000218733	**n**	0.00000028
Dead path length	**ldp**	100 mm	**ldp**	1 mm
Refractive index of air initial	**n i**	1.000219417	**n i**	0.00000028
Refractive index of air final	**n f**	1.000218733	**n f**	0.00000028
Length of line in scale in pixels	**lp**	2 pixeles	**lp**	0.1 pixeles
Rate factor of pixels to micrometers	**f**	0.004 um/pixeles	**f**	0.01 um/pixeles
Angle between scale and laser beam	**θ**	0.000382 º	**θ**	0.000277 º
Distance between scale and laser beam	**la**	50 mm	**la**	1 mm
Yaw angle movement of carriage along bench	**β**	0.005277 º	**β**	0.0003 º
Distance between cube corner and ccd camera	**ld**	100 mm	**ld**	1 mm
Pitch angle movement of carriage along bench	**τ**	0.008611 º	**τ**	0.0003 º

Table 1.

The influence of scale temperature and thermal expansion coefficient for scales of 3 m are the greatest contributors to uncertainty, this is show in the figure 9. If scales of minor length are measured, the uncertainties due to the refractive index of air and Abbe error become important. Nevertheless his contributions are small, and is less of 10 % of total uncertainty for deviations of 1º C, and when the deviations are of 5º C the contributions are less of 2 %.

This effect could be reduced taken into account the thermal expansion coefficient of the scale. This could be done measuring the coefficient, with a good enough uncertainty. For instance if the coefficient is measured with an uncertainty of 0,1 ppm/ºC the uncertainty is improved as show in the figure 10.

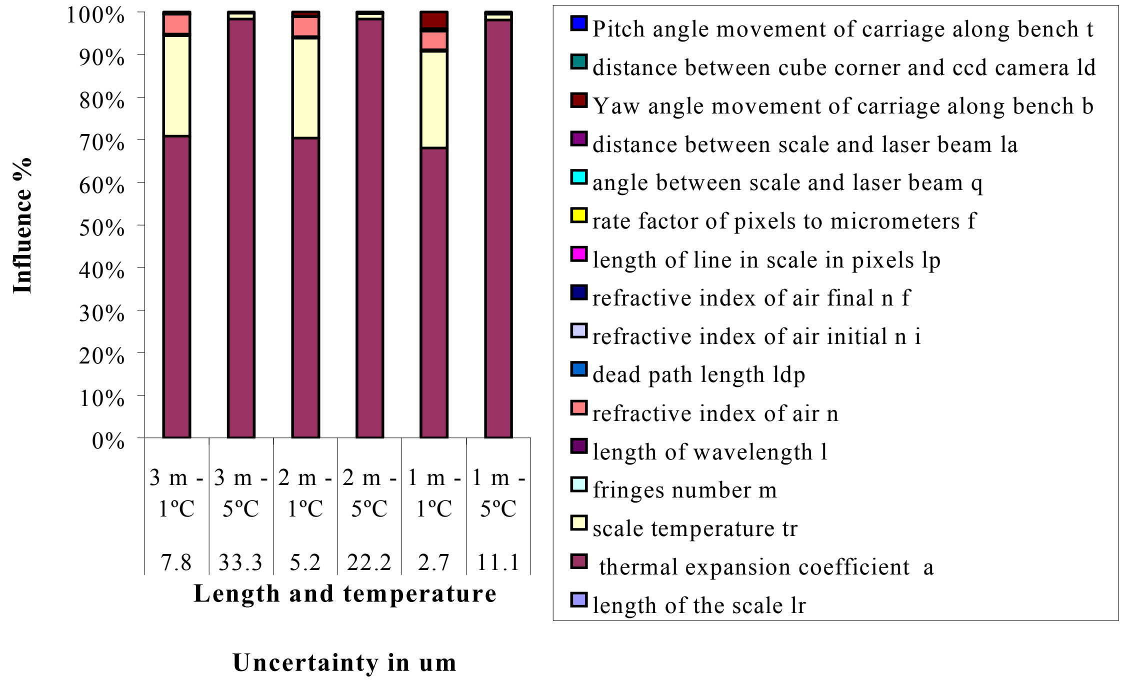


Figure 9. Influence of scale temperature and thermal expansion coefficient in uncertainty.

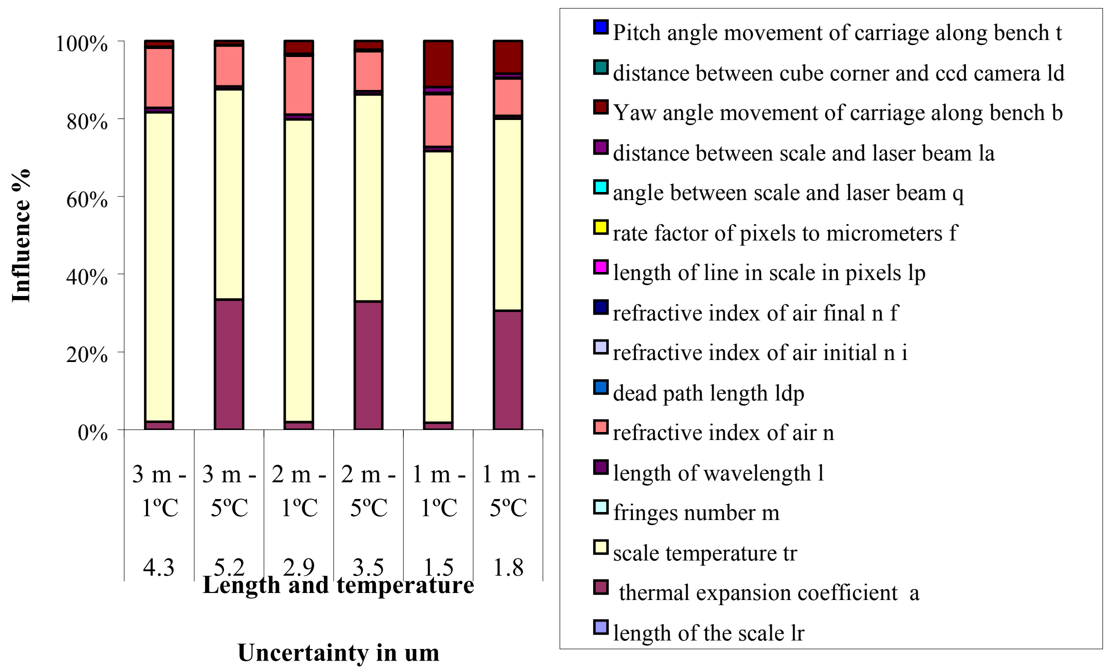


Figure 10. Influence of scale temperature and thermal expansion coefficient in uncertainty improve the uncertainty of measurement of thermal expansion coefficient

VIII. CONCLUSIONS

One system for automatic linear scale calibration was developed at CENAM applying a novel approach for the detection of lines on scale using a vision system and a interferometric measurement. The vision system already has been probing in another measurement applications, due its accuracy and well detection of lines, obtaining and repeatability better that 100 nm. This encourage in order to improve the capability of this system.

The following stage of the project will involve the final comparison of the results with the aid of an intercomparison with other laboratories with similar or better measuring systems. One option to decrease the measuring uncertainty is measuring the thermal expansion coefficient, with an uncertainty at least of 1×10^{-7} $^{o}C^{-1}$, this can be noted in the uncertainty budget that show the importance of this input quantity and its uncertainty.

In order to offer calibration services the implementation of the quality system is necessary following the guidelines of ISO 17025.

IX. REFERENCES

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