Traceability of line scales using image processing

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Abstract: Metrological traceability, is defined as the "property of a measurement result that allows the result to be related to a reference through an unbroken chain of calibrations, each contributing to the measurement uncertainty." Calibrating a line scale consists of determining the distances between the center of the marks along its length. This type of calibration is usually performed by a comparative method, where a standard scale of higher accuracy is positioned next to the scale to be calibrated, and its marks are visually compared using a graduated magnifying glass. This methodology has some points that can be improved in order to make the calibration faster, less dependent on an operator. The calibration method proposed and presented in this paper uses computer vision techniques for calibrating line scales, turning a digital camera into a measurement standard with its traceability referenced to a length standard. The method consists of applying an image registration technique, where images are captured in sequence along the scale, and redundant points in the images are automatically. The proposed procedure is capable of generating results with uncertainties ranging from 0.05 mm to 0.30 mm for scales up to 1 meter.

Keywords: Metrology, Traceability, Computer Vision, Image Processing.

1. Introduction

Traditionally, the calibration of line scales is performed through visual comparison between the scale to be calibrated and a standard scale, which are placed side by side, and the distances between the scale marks are measured using a graduated magnifying glass. However, as this process is subject to limitations and significant influences that affect the measurement result, as well as the considerable time required for the process.

Therefore, aiming for reliable calibrations in less time, studies to employ computational tools and artificial intelligence in these processes have been developed. According to the article published by Yadayan and Ozgur (2014) [1], it is possible to measure tapes and rulers up to 5 meters long using computer vision, where it is used to determine the centers of each mark. In this system, the scale remains supported on fixed supports while a camera moves along a guide with controlled movement by a stepper motor, and its displacement is measured by a linear encoder. Combining the displacement information with the positioning of the marks in the image allows for the determination of the distances between the marks on the scale, a calibration method also presented by Bong et al. (2013) [2].

From this perspective, it is possible to perform calibration using various technological resources. Through a PLC (Programmable Logic Controller), sensors, a mechanical displacement system, and image processing software, Santos, Silva, and Galdino automated the calibration process of tapes and line scales, bringing improvements and reducing human labor, as presented in Santos et al. (2015) [3]. The use of other equipment also contributes to the advancement of this field, such as coordinate measuring machines (CMM), lasers, advanced technology cameras, as well as various software capable of image processing and analysis [4-5].

The significant potential that computer vision has to contribute to the improvement of the calibration process for tapes and line scales is evident. Based on this, the present study aims to propose a system for calibrating line scales using computer vision. The proposal is to use only image information for measuring the distances between the marks, without the need for a displacement measurement system, with the focus of making the system more affordable while maintaining the reliability of this type of calibration.

2. Proposed Method

The proposed measurement system can be divided into three stages: Image Acquisition, Image Processing and Analysis, and Results Obtaining. These stages are described in detail below.

2.1 Image Acquisition

For image acquisition, a Basler scA1000-30gm camera was used, featuring a CCD sensor and Gigabit Ethernet (GigE) interface technology, with a resolution of 1034x779 pixels. Illumination was provided by an LED panel to ensure uniform lighting during image acquisition.

The complete setup can be observed in Figure 1. To position the camera, a height-adjustable support was used to achieve proper focus. The scale was positioned and its alignment and movement were ensured using support points utilizing the holes on an optical table. Lastly, a dark-colored paper was used as the background for the images to enhance contrast, and the LED panel was positioned accordingly.

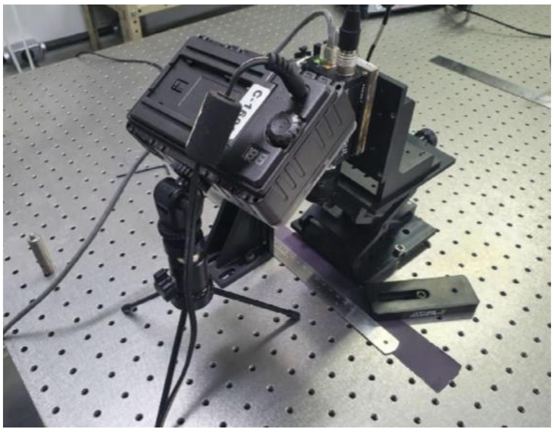

Figure 1. Experimental setup for capturing images of the scale.

2.2 Image processing and analysis

The first step in the processing is the detection of interest points using the Harris method [6]. In this stage, starting from a user-selected region of interest (Figure 2.a), the Harris method is applied to identify points that may be significant in the image (Figure 2.b), such as corners or lines. This procedure is performed for each pair of consecutive images, where the user selects regions that repeat in these two images (Figure 2.c).

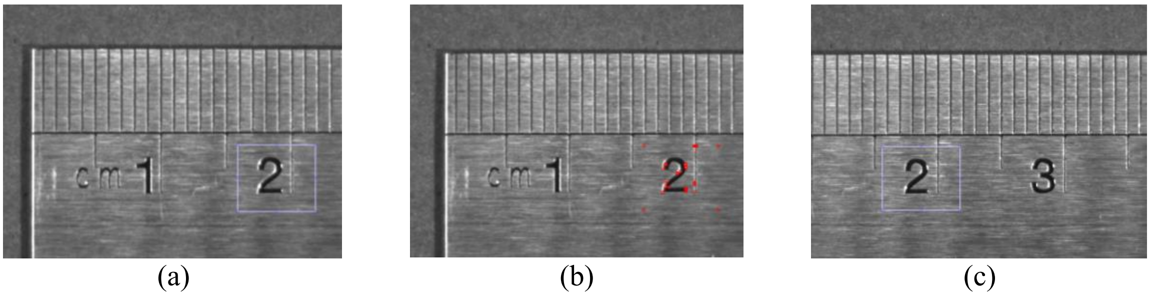
(a) (b) (c)

Figure 2. Steps of the Harris algorithm - (a) Region of interest in a first image; (b) Points found using the Harris algorithm; (c) Procedure in the next image.

The second step of the processing is to identify which points are identical in the two images. To do this, all the points from the first image are separated, and the following methodology is followed step by step. The first point obtained by the Harris algorithm in the first image is identified and set as the central pixel of a 50 x 50 pixel matrix. Once this matrix is fixed, it is compared with the 50 x 50 matrices of all the points identified by Harris in the second image. For each comparison, a Pearson correlation value is calculated. This procedure is performed for all possible combinations of the points identified in the two images. The choice of a 50x50 matrix size is empirical and may vary depending on the user's choice, considering the image sizes and level of detail.

In a subsequent step of the algorithm, the 10 points with the highest correlation values obtained are selected, and these points are considered identical in the two images. To determine the movement between the points in the two images, a linear transformation that maps the points from the first image to the second image is calculated. Based on this linear transformation, a new image is generated where the first image is completely written, and the pixels from the second image are relocated according to the obtained linear operation (Figure 3.a).

This new image becomes the initial image, and the processing is repeated until the last captured image of the scale (Figure 3.b).

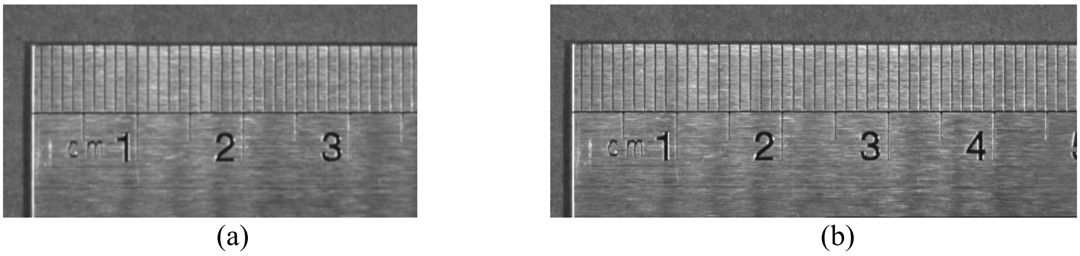
(a) (b)

Figure 3. Image merge sequence – (a) merge of two images, (b) merge of three images.

2.3 Obtaining the results

The last step is the determination of the scale's lengths. The advantage of this method is that, at this point, the user has the complete scale in a single image. Therefore, it is possible to determine the distances between the scale marks using only the image. To achieve this, the image is binarized using the Otsu method [7], where the scale marks are entirely in black color (pixels with a value of zero), and the background is entirely white, with pixels having a value of one. Thus, the centers of the scale marks are determined, and their distances are measured in pixel units.

The conversion of the pixel measurements, as well as the traceability of the method, are provided by a calibrated scale. A calibrated scale is measured, and based on its maximum length, the pixel value for the camera configuration is determined. This value is used as a reference for determining the other distances on the scales to be measured.
The procedure is reproducible for scales that have the same thickness as the reference scale used.

3. Measurements

To test the developed methodology, a calibrated 600-millimeter scale was used. The scale was set up on the previously described setup and went through the entire process, starting from image capture, point detection and merging the image into one, and finally, the results obtaining methodology.
For this particular test, the scale used was the actual reference scale, and the pixel length for the measurement configuration was determined using the calibration point of 600 mm on the scale.
Consequently, for the obtained results, the deviation from the calibration certificate for the 600 mm point was exactly zero. However, it was possible to observe the behavior of the proposed method for determining the other distances and their associated uncertainties.
The measurement results are presented in Table 1, showing the positions of the centers of the scale marks in pixel quantities. For this experiment, the distances starting from the 60 mm point were used as references since the calibration certificate did not specify how the zero point was determined from the top of the scale. Therefore, the 60 mm point was adopted as the reference to avoid introducing errors in the measurement procedure.

Table 1. Positions of the centers of the scale marks in the image for the three measurement runs.

Length	Run 1	Run 2	Run 3
60 mm	2412	2424	2470
120 mm	4711	4723	4767
180 mm	7005	7019	7065
240 mm	9300	9311	9358
300 mm	11596	11603	11652
360 mm	13891	13897	13945
420 mm	16185	16193	16240
480 mm	18480	18488	18536
540 mm	20775	20782	20830
600 mm	23072	23076	23126

As mentioned earlier, the pixel calibration was performed by comparing the distance measured in the image between the 600 mm and 60 mm points to the corresponding distance reported in the calibration certificate, resulting in the following model according to Equation 1.

$$L_p = \frac{L_{540\,mm}}{Np_{540\,mm}} \tag{1}$$

Where L_p is the pixel length, L_{540mm} is the length specified in the calibration certificate between the 600 mm and 60 mm marks, and N_{p540mm} is the number of pixels between these two marks.
The obtained result for Lp was 0.02614 mm, with a standard deviation of 0.00001 mm among the three measurements. Using this pixel length value, all the lengths of the scale can be determined using Equation 2.

$$L_r = L_p.(P_i - P_0) \qquad (2)$$

Where L_r is the measured length in millimeters between points P_0 and P_i, L_p is the previously calibrated pixel length, P_0 is the reference mark (60 mm in the this test), and P_i is the point for which the distance relative to the 60 mm mark is desired.

The chosen values were at intervals of 10% of the total length of the scale, similar to those in the calibration certificate, to comparison and validation of the results. The results are shown in Table 2.

Table 2. Mean and standard deviation results for the three measurements conducted.

Length	Result (mm)	Stdev (mm)
60 mm	0,000	0.000
120 mm	60.072	0.030
180 mm	120.083	0.030
240 mm	180.025	0.015
300 mm	239.984	0.066
360 mm	299.943	0.080
420 mm	359.928	0.054
480 mm	419.921	0.052
540 mm	479.889	0.066
600 mm	539.891	0.105

As a first assessment of the results obtained by the proposed method, an analysis of the measurement uncertainty was conducted.

3.1 Measurement Uncertainty

An important parameter to assess the applicability of the method is the measurement uncertainty. From the mathematical models used to determine the pixel size and distances on the scale, sources of uncertainty can be identified. The details of the uncertainties for pixel calibration are provided in Table 3.

Table 3. Uncertainty budget for pixel calibration.

Input quantity	Estimate	*p.d.f*	u(x*i*)	c_i	u(y) (mm)	ν
	mm	Normal	mm	1/pixels		
L_{540mm}	0.1	2	0.05	0.000048	0.0000024	inf
	pixels	Uniform	pixels	mm/pixels^2		
Type A	2.517	1.732	1.452	0.0000013	0.0000018	2
	pixels	Uniform	pixels	mm/pixels^2		
$Np_{540\ mm}$	2	1.732	1.452	0.0000013	0.0000018	inf
				$\mathbf{u_c}$ =	0.0000036 mm	

The presented result shows a combined uncertainty of 3.6 nm, which is quite small compared to the uncertainties typically encountered in this type of measurement. This low contribution is due to the large number of pixels that describe the measured distance between the 60 mm and 600 mm marks, which was approximately 20,000 pixels. Additionally, the mathematical model for pixel length calibration includes sensitivity coefficients that place this high value in the denominator, thereby reducing its effect for shorter lengths and improving the measurement result.

By using this uncertainty value, it is possible to determine the uncertainties for the other measured lengths of the scale. The influencing factors, their respective contributions, and the complete assessment are provided in Table 4 and Table 5. As examples, the smallest and largest measured lengths were used: 60 mm and 540 mm, which represent the distances between 60 mm and 120 mm, and 60 mm and 600 mm, respectively.

Table 4. Uncertainty budget for 60 mm calibration

Input quantity	Estimate	*p.d.f*	u(xi)	c_i	u(y) (mm)	ν
	mm	Normal	mm	1		
Type A	0.03	1.732	0.0174	1	0.01742	2
	pixels	Uniform	pixels	mm		
$\boldsymbol{P_0}$	1	1.732	0.0577	0.0261	0.01509	inf
	pixels	Uniform	pixels	mm		
$\boldsymbol{P_i}$	1	1.732	0.0577	0.0261	0.01509	inf
	mm	Normal	mm	pixels		
$\boldsymbol{L_p}$	0.0000036	1	$3.6.10^{-6}$	2299	0.00817	inf
				$\mathbf{u_c}$ =	0.0278 mm	
				$\boldsymbol{\nu_{eff}}$ =	15	
				k =	2.1953	
				$\mathbf{U_{95.45\%}}$ =	0.061 mm	

As shown in Table 5, it can be observed that the measurement uncertainty is highly dependent on the measured length. This is because the uncertainty due to pixel size accumulates as more pixels are used in the measurement. Looking at the uncertainty assessment for a length of 60 mm, as shown in Table 3, the largest contribution comes from the Type A measurement uncertainty. However, in the example of the 540 mm distance point, the largest contribution shifts to the pixel length, which has a sensitivity coefficient tied to the number of pixels used in the distance determination.

Table 5. Uncertainty budget for 540 mm calibration

Input quantity	Estimate	*p.d.f*	u(xi)	c_i	u(y) (mm)	ν
	mm	Normal	mm	1		
Type A	0.105	1.732	0.060	1	0.060	2
	pixels	Uniform	pixels	mm		
P_0	1	1.732	0.0577	0.0261	0.01509	inf
	pixels	Uniform	pixels	mm		
P_i	1	1.732	0.0577	0.0261	0.01509	inf
	mm	Normal	mm	pixels		
L_p	0.0000036	1	$3.6.10^{-6}$	20660	0.0734	inf
				$\mathbf{u_c}$ =	0.097 mm	
				$\mathbf{\nu_{eff}}$ =	14	
				k =	2.2118	
				$\mathbf{U_{95.45\%}}$ =	0.22 mm	

Finally, applying the same analysis procedure to all the measured distances on the scale, the following results were obtained (Table 6).

Table 6. Final results for the line scale calibration

Length	Result (mm)	$U_{95,45\%}$ (mm)
60 mm	0.000	0.043
120 mm	60.072	0.063
180 mm	120.083	0.068
240 mm	180.025	0.067
300 mm	239.98	0.13
360 mm	299.94	0.16
420 mm	359.93	0.13
480 mm	419.92	0.14
540 mm	479.89	0.16
600 mm	539.89	0.22

4. Method validation

In order to validate the results of the proposed methodology, the distances measured using the method were compared with the distances from the calibration certificate of the scale. To assess compatibility or incompatibility between the results, the parameter of normalized error was adopted. This parameter is widely used in metrology for the validation of analytical methods, as stated in document DOC-CGCRE-008 by Inmetro, 2016 [7]. The normalized error is calculated according to Equation 3 and compares the results obtained by the two methods and their respective uncertainties. The results can be considered compatible when the value of the normalized error is less than one.

$$EN = \frac{Vm - Vr}{\sqrt{U_{Vm}^2 + U_{Vr}^2}} \tag{3}$$

Where V_m is the measured value to be validated, V_r is the reference value for comparison, and in the denominator are their respective expanded uncertainties.

Table 7 shows the values and uncertainties obtained by the proposed method and the calibration certificate, along with their respective normalized errors.

Table 7. Results of the validation of the proposed method.

New Method		Reference		EN
Vm (mm)	U (mm)	Vr (mm)	U (mm)	
0.000	0.043	0.0	0.1	0.002
60.072	0.063	60.1	0.1	0.236
120.083	0.068	120.0	0.1	0.689
180.025	0.067	180.0	0.1	0.205
239.984	0.129	240.0	0.1	0.100
299.943	0.158	300.0	0.1	0.307
359.928	0.129	359.9	0.1	0.168
419.921	0.139	419.9	0.1	0.124
479.889	0.162	479.9	0.1	0.058
539.891	0.215	539.9	0.1	0.037

As observed in the column corresponding to the normalized error, all the obtained values were smaller than one. With a maximum value of 0.7, indicating compatibility between the obtained results and the reference values from the calibration certificate.

Therefore, it can be concluded that the method can provide reliable and traceable results.

5. Conclusions

The main objective of this study was to present research that aims to propose a new methodology for the calibration of graduated scales. In this first stage, a method for the calibration of graduated scales was studied, where the novelty lies in the ability to calibrate a scale without the need for a displacement measurement system and without the requirement of direct visual comparison between an object and a standard.

The proposed method is based on reconstructing the entire scale in a single image using computer vision techniques. From this reconstruction, it is possible to obtain the distances between all the scale marks with sufficient resolution for measurements to be performed solely through pixel counting.

The initial tests conducted, as presented in this work, demonstrate that the method can obtain reliable and compatible results with a calibrated reference standard.

In the next stage, the applicability of the methodology will be evaluated for standards with longer lengths and for the measurement of tapes.

6. References

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