Chapter

Data Acquisition System for Calibration of Handheld Digital Multimeters through Digital Image Processing

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Abstract

The purpose of the project was to develop an automatic system for the acquisition and recognition of measurements taken by handheld digital multimeters through the use of images; this was proposed in order to improve their calibration process in the magnitudes of direct and alternating current, direct and alternating voltage, and electrical resistance. Thus, a system was developed to automatically capture, process, and recognize the values associated with multimeter readings in its calibration process, divided into three stages: The first stage consisted of creating a database with information of the multimeter models to be calibrated, the standard instrument (evaluating the feasibility of using it in the process), and the calibration points. In the second stage, an algorithm was developed to identify and classify the values displayed on the under-test multimeter. In the third stage, the process of uncertainty estimation, reporting, and evaluation of the validity of the results was carried out. From this last subprocess, it was determined that the capture and uncertainty estimation system is adequate to perform the calibration of the evaluated handheld digital multimeters.

Keywords: digital handheld multimeter, multimeter calibration, image processing, uncertainty estimation, validity of results

1. Introduction

The concept of metrology, as expressed by Marbán et al. [1], has been present in human life since the establishment of the firsts comparisons. To measure is, on a basic way, an action of comparing a something unknown (a quantification of a magnitude that we do not know), with something with a known value (reference quantification that we know). The calibration process of any measurement instrument represents a significantly important component to validate the indication given by equipment. International vocabulary of metrology [2] defines calibration as:

> *operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication. (p. 28)*

To give conformity to their measurement processes or following the guidelines of specific procedures, companies in the industrial sector and laboratories that perform work related to metrology require to calibrate their instruments periodically. The whole process involves both administrative and technical tasks that require specific times for its execution, and any human process is prone to incur in any type of error. However, it has the possibility of being automated, even if it is partially, reducing the duration and the possibilities of error of the process, guaranteeing in the same way the quality of the obtained results.

Particularly in electricity, electrical current intensity represents the base unit from which important units such as electrical voltage, electrical resistance, and capacitance, among others, are derived. An alternative to measuring these physical phenomena is by the use of digital multimeter which, according to Fluke Corporation [3], is an "electronic meter for making electrical measurements," which has a wide range of special measurement functions.

Digital technology is increasingly present in human life, and as a result, the industry has been involved in a digital transformation, which leads to the use of new techniques that help to provide greater reliability and accuracy in the various production processes, reducing time, probability of error occurrence, and, likewise, costs per process. The use of this technology in metrology is particularly convenient since it not only allows the improvement of the internal processes of each laboratory but also opens the way to a substantial improvement in the communication and information management of customers, laboratories, regulatory bodies, national institutes, and other entities related to metrology. As mentioned by Bauer et al. [4], the technological growth curves of both automation and metrology have increased significantly fast and are increasingly influenced by micro, nano, and even femto technologies.

2. Database of multimeters and measurement standards

For the construction of the database, information related to the accuracy of the instruments to be calibrated, the accuracy of a generating instrument, and the relationship between both parts was taken into account, to determine the feasibility of using such calibrator as a working standard, in each of the calibration points.

2.1 Test multimeters and information of interest

For the project, three different models of handheld digital multimeters were used: Fluke 87-V, Fluke 112, and Fluke 179.

The three models do not have a communication protocol and, therefore, are suitable for the development of the recognition of its indication by image processing. Additionally, other influencing factors are considered to evaluate whether the proposed standard instrument (Fluke 5500A calibrator) is suitable for the work.

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2.1.1 Maximum allowable error of the models

The user's manuals of digital multimeters refer to information corresponding to the accuracy of the instrument or, in other words, its maximum permissible error of measurement or accuracy. This characteristic is commonly given as the sum between a percentage of the measurement and a predetermined number of counts and is calculated as follows:

$$EMP = \pm[\%of\ \ reading \cdot V_n + Counts \cdot Resolution] \tag{1}$$

2.2 Calibration procedure

Laboratories must have methods or procedures for calibration activities, verifying that they can be adequately developed before putting them into operation (ISO/IEC 17025:2017 numeral 7.2.1 [5]). Thus, the document written jointly by the National Metrology Institute of Colombia—INM, members of the Colombian Metrology Network—RCM, and the National Accreditation Body of Colombia—ONAC is used. This is called "GUÍA PARA LA CALIBRACIÓN DE MULTÍMERTOS DIGITALES 4 5/6 (50000 CUENTAS) – INM\GTM EM-CCA\01" [6] and was published in July 2019, in its version number 1.

The purpose of the document is to provide recommendations for calibrating digital multimeters with resolution not greater than 4 5/6 digits (50,000 counts). It covers

Measurement function: D.C. voltage					
Test points		**Accuracy**		**Traceability assessment**	
Range	**Test point**	**Standard**	**Multimeter**	**TAR**	**State**
Model: Fluke 179					
600 mV	0 mV	***0.003000 mV***	***0.200000 mV***	66.67	**Pass**
600 mV	60 mV	***0.006600 mV***	***0.254000 mV***	38.48	**Pass**
1000 V	100 V	***0.0060 V***	***2.1500 V***	358.33	**Pass**
1000 V	900 V	***0.0510 V***	***3.3500 V***	65.69	**Pass**
Model: Fluke 87-V					
600 mV	0 mV	***0.003000 mV***	***0.100000 mV***	33.33	**Pass**
600 mV	60 mV	***0.006600 mV***	***0.160000 mV***	24.24	**Pass**
1000 V	100 V	***0.0060 V***	***1.0500 V***	175.00	**Pass**
1000 V	900 V	***0.0510 V***	***1.4500 V***	28.43	**Pass**
Model: Fluke 112					
600 mV	0 mV	***0.003000 mV***	***0.200000 mV***	66.67	**Pass**
600 mV	60 mV	***0.006600 mV***	***0.230000 mV***	34.85	**Pass**
600 V	60 V	***0.0038 V***	***0.2300 V***	60.53	**Pass**
600 V	540 V	***0.0312 V***	***0.4700 V***	15.06	**Pass**
Where italic and bold numbers are used to assess the state of traceability.					

Table 1.
Traceability accuracy ratio (TAR) assessment for D.C. voltage.

the required quantities and estimates the measurement uncertainties, based on the guide to the expression of uncertainty in measurement (GUM) [7].

2.3 Accuracy ratio

For each of the functions to be evaluated, the corresponding calibration points and relation of specifications were established. For each of the points, the Fluke 5500A calibrator has sufficient accuracy to perform the process, allowing the use of the multimeters mentioned as sample for the development of the data acquisition system from images. **Table 1** shows the evaluation of the maximum and minimum points considered by the procedure in the D.C. voltage function; however, this exercise was performed for each of the points to be calibrated for each multimeter.

According to the accuracy evaluation, it is concluded that the Fluke 5500A calibrator is suitable for calibrating the three multimeters under test.

3. Recognition of multimeter readings

3.1 Initial conditions for processing

Before implementing the algorithm for digit recognition, a compartment with internal illumination was created, where the multimeters are positioned, such that the illumination conditions for image processing are standardized, without the presence of exogenous disturbances given by external illumination sources.

The side holes of the compartment (see **Figure 1**) are intended to allow the movement of the multimeter's fastening element and the connection cables between the standard equipment and the instrument under calibration. The front hole, on the other hand, is used to locate the camera that captures the photos of the multimeter display.

The image acquisition of the multimeter to be calibrated was performed with a mobile device camera of 108 megapixels. The communication between the camera and the image processing system is done through an application that allows using the camera of the mobile device as a complement to the computer that will be used for the processing.

Figure 1.
Multimeter location compartment.

3.2 Recognition algorithm

The digit recognition system of the digital multimeters was made from four subsystems or processing subsequences shown in the diagram of **Figure 2**. The first stage is responsible for making a first cleaning and thresholding of the image; in the second stage, the segmentation or partitioning of the display is performed, with respect to the rest of the image; followed by, in the third section, the recognition and separation of each of the digits shown by the multimeter is performed to finally recognize and locate the decimal point of the value shown on the display.

3.2.1 Initial processing

Initial processing on the captured image is divided into standardizing the size of the original image, changing its color scale to gray scale, applying filters that remove some unwanted information for processing, and thresholding the image from edge recognition.

Initially, in order to ensure that the display recognition parameters do not vary in the event of a change in the acquisition camera, the image size was standardized and set to a width of 1280 pixels by 720 pixels high. Additionally, the photos captured by the camera are color images, an aspect that does not provide relevant information to the proposed recognition process. Thus, in order to reduce the size of the images to improve the processing speed, a gray space transformation is performed as shown in **Table 2**.

Once the gray scale image is obtained, it is smoothed or blurred from a normalized matrix (kernel), which follows the form:

$$k_{Blur} = \frac{1}{9} \cdot \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \tag{2}$$

The purpose of this smoothing is to reduce information related to possible scratches or other minor conditions of the multimeter and the environment that may alter the subsequent thresholding as presented in **Table 3**.

For binarization or thresholding, the Canny edge detector was used, which makes use of the intensity gradients of the image and, according to established upper and lower limits, detects the edges of the processed figure. In this way, the edges will be colored in white and the rest of the pixels will be black.

As an additional process to binarization, it was necessary to implement a morphological operation of dilation (as exemplified in **Figures 3** and **4**), which was performed with the purpose of closing the edges of the display.

3.2.2 Segmentación del display

With the image already binarized, we proceed to find the existing contours and extract the associated information so that the section of the display can be

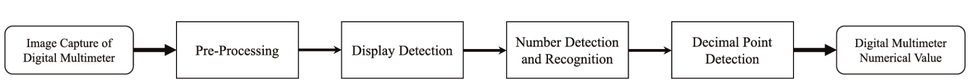


Figure 2.
General processing block diagram.

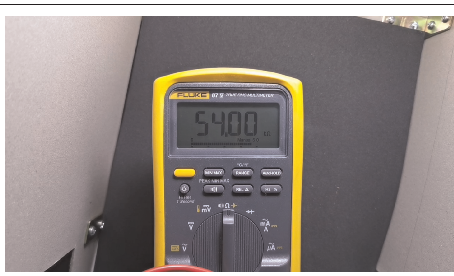
Fluke 112 capture	
Color scale	Gray scale
	
Size: 835 kB	Size: 313 kB
Fluke 179 capture	
Color scale	Gray scale
	
Size: 1439 kB	Size: 494 kB
Fluke 87-V capture	
Color scale	Gray scale
	
Size: 1286 kB	Size: 447 kB

Table 2.
Size difference due to the color transformation.

discriminated from the rest of the capture. Five values of interest are extracted from the contours. The first one corresponds to the area of the contour found that will be compared with two reference thresholds, with which it is determined if the area found can be attributed to the multimeter display, or if it is part of another element of the image; the following two parameters correspond to both the width and the height of the contour and will be used to determine a variable of interest called "aspect ratio" that corresponds to the existing proportion between the width and the height, which is given as follows:

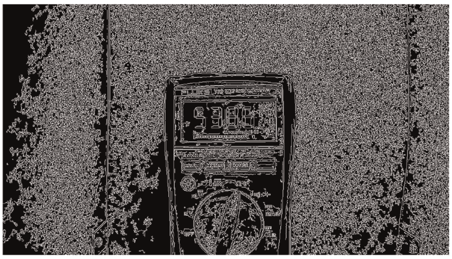
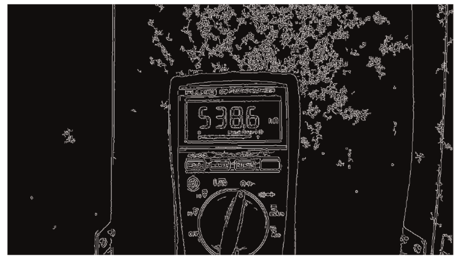
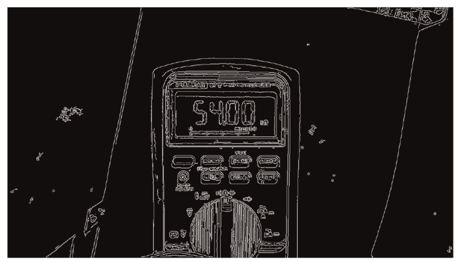
Fluke 179 thresholding	
Without smoothing	With smoothing
	
Fluke 87-V thresholding	
Without smoothing	With smoothing
	
Fluke 112 thresholding	
Without smoothing	With smoothing
	

Table 3.
Importance of image smoothing.

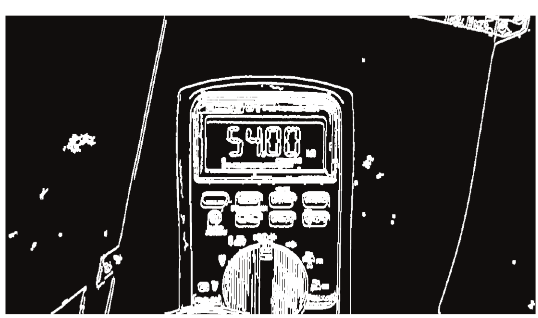


Figure 3.
Model 87-V dilatation.

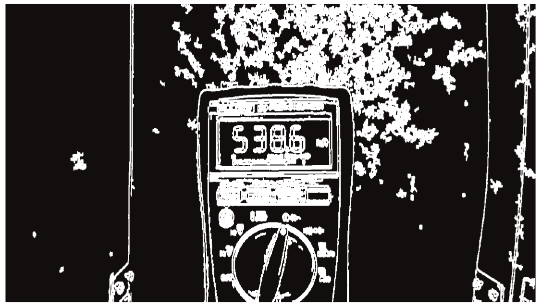


Figure 4.
Model 179 dilatation.

$$R_{Aspecto} = \frac{Width\ of\ Contour}{Height\ of\ Contour} \tag{3}$$

Measurements were made of both the width and height of the displays of the three selected multimeters, with these approximate values the corresponding aspect ratio associated with each model was calculated, the three values were averaged and experimentally a tolerance associated with that average value was determined, such that in most cases it detects the display outline satisfactorily. The dimensions of the three displays are shown in **Table 4**.

From experimental tests performed on the selected multimeters and taking into account the calculated aspect ratio, an allowable tolerance of ± 0.4 was established, which determined that the upper and lower limits with which the experimental aspect ratio will be compared are 2.6 and 1.8, respectively.

Once these comparison conditions are established, each of the contours found by the algorithm is evaluated and the one that complies with both the area and the aspect ratio will correspond to the digital multimeter display and this area will be demarcated by the algorithm, as shown in **Figures 5–7**.

Subsequently, the selection associated with the display is segmented from the rest of the image, resulting in the clipping of the multimeter display (see **Figures 8–10**).

3.2.3 Segmentation of numerical values

Once the multimeter display has been segmented, each of the numerical values corresponding to the measurements of the various functions to be calibrated is recognized. Thanks to the fact that the selected models present their values from seven

Model	Width	Height	Aspect ratio
Fluke 87-V	64 mm	28 mm	2.286
Fluke 112	51 mm	24 mm	2.125
Fluke 179	61 mm	28 mm	2.179
Mean			2.197

Table 4.
Aspect ratio of evaluated displays.

Figure 5.
Model 87-V contour of interest.

Figure 6.
Model 179 contour of interest.

Figure 7.
Model 112 contour of interest.

segments that follow the shape of the **Figure 11**, a detection algorithm is proposed in which initially each segment is separated from the rest and it is evaluated if it is on or not, making use of the intensity of the pixels.

A labeling of the numbers from zero to nine that will be treated as reference to be later compared with the display to be evaluated is performed. Values of one (1) correspond to segments that are on; on the contrary, values of zero (0) indicate that the value of the segment is off. The labeling of each one of the numbers was established as presented in the **Table 5**.

Figure 8.
Model 87-V segmented display.

Figure 9.
Model 179 segmented display.

Figure 10.
Model 112 segmented display.

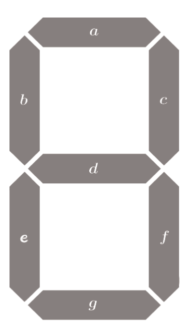


Figure 11.
Seven segments display.

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	Location						
Number	***a***	***b***	***c***	***d***	***e***	***f***	***g***
0	1	1	1	0	1	1	1
1	0	0	1	0	0	1	0
2	1	0	1	1	1	0	1
3	1	0	1	1	0	1	1
4	0	1	1	1	0	1	0
5	1	1	0	1	0	1	1
6	1	1	0	1	1	1	1
7	1	0	1	0	0	1	0
8	1	1	1	1	1	1	1
9	1	1	1	1	0	1	1

Table 5.
Reference label.

When the reference vectors representing each of the numbers have been constructed, we continue with the processing of each of the digits of the display separately.

The display cutout is subjected to thresholding and subsequent morphological operations to highlight the geometric characteristics of the digits in the image (as shown in the **Figure 12**).

Then, a second cropping is performed within the display so that only the numerical values to be evaluated and the point are shown (see **Figure 13**). For this, a second

Figure 12.
Display thresholding.

Figure 13.
First cut of the display.

contour search is performed to extract information such as height, width, and the corresponding aspect ratio (determined from the Eq. (3)) of each of the detected objects. From estimates made experimentally, it was determined that the height of the digits ranges between 200 and 600 pixels, the width has an approximate value of less than 300 pixels, and the aspect ratio is less than 0.5 (ranging between 0.1 and 0.2 for the representation of the number 1).

With the mentioned conditions, the numerical values corresponding to the measurement are enclosed in rectangles (see **Figure 14**) and separated as shown in **Figures 15–18**. Finally, the last sequence is initialized for number recognition.

3.2.4 Number recognition

After each numerical value of the display associated with the measurement has been segmented, the images are divided into seven subsections corresponding to the seven segments of each display. Afterward, the number of white pixels and the number of black pixels in each division are counted, which evaluates whether the segment is on or off (a record of 1 is kept if it is on, or 0 if it is off) as presented in the **Table 6**; a vector or label is obtained that will represent the number and this value will be compared with the references presented in the **Table 5**.

Figure 14.
Digits location.

Figure 15.
First digit separation.

Figure 16.
Second digit separation.

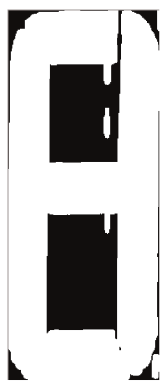


Figure 17.
Third digit separation.

Figure 18.
Fourth digit separation.

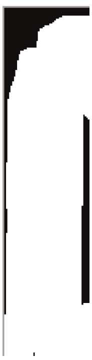
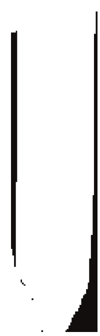
White pixel count	
Segment *a*	Segment *d*
	
White pixel percentage: 65.38%	White pixel percentage: 91.38%
Segment *b*	Segment *c*
	
White pixel percentage: 85.68%	White pixel percentage: 16.11%
Segment *e*	Segment *f*
	
White pixel percentage: 23.39%	White pixel percentage: 88.87%
Segment *g*	Label value
	1101011
White pixel percentage: 72.37%	

Table 6.
Pixel count in each segment of number five.

This process is repeated with each of the values found and thus the numerical value associated with the photo of the digital multimeter indication will be determined.

Figure 19.
Decimal point location.

Figure 20.
Value recognized by the algorithm.

3.2.5 Recognition and decimal point location

A rectangular area ($80x40$ *Pixels*) for evaluation is associated to each segmentation in which the number of white pixels will be counted as well. If the count exceeds half of the total pixels, then the decimal point is considered to be located in that space (as illustrated in the **Figure 19**).

With the recognition of both the numerical values and the decimal point, the numerical value displayed on the digital multimeter is obtained. **Figure 20** illustrates the recognition performed by the algorithm.

4. Data acquisition and estimation of uncertainties

The purpose of the data acquisition system is to capture the following data: Nominal value to be generated by the standard instrument and 12 readings corresponding to the instrument under calibration. These will be sent to an Excel sheet in charge of making the respective calculations necessary for the process.

The scheme proposed in **Figure 21** represents the proposed step-by-step approach for reporting measurement errors and their associated uncertainties in the calibration of digital multimeters.

From the data captured from the digital multimeter, the average value and the associated standard deviation are calculated; from the calculated average and the nominal value, the bias of the measurement corresponding to the mathematical model associated with the calibration is established [6]:

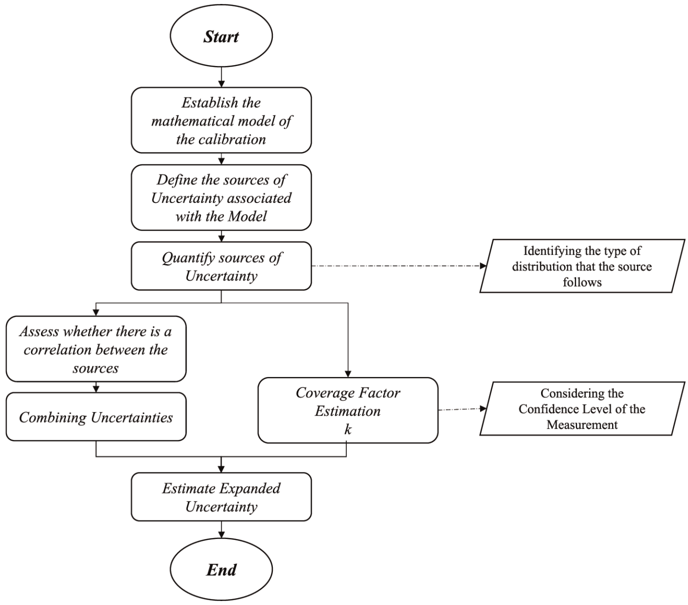


Figure 21.
Scheme to establish the measurement result.

$$E = \overline{V}_x - V_s \tag{4}$$

where E refers to the measuring bias, $\overline{V}_x$ corresponds to the mean value of the multimeter indications and V_s corresponds to the nominal value of the standard instrument. Taking into account the possible deviations due to the standard system and the instrument under calibration, the model is complemented as presented in Eq. (4).

$$E = \left(\overline{V}_x + \delta V_x\right) - (V_s + \delta V_s) \tag{5}$$

where δV_x corresponds to the correction due to the resolution of the multimeter and δV_s corresponds to the corrections of the standard system due to different effects. The corrections due to the zero measurement were not taken into account in the exposed model because this was taken as an independent measurement point. In summary and taking into account the reference document for calibration, a representation of the sources of uncertainties involved in the process is shown in **Figure 22**.

By means of the propagation of uncertainties for uncorrelated input variables established by (BIPM/JCGM) Bureau International de Pois et Measure Joint Committee for Guides in Metrology [7], the corresponding uncertainty associated with the measurement is obtained, such that:

$$u^2(E_x) = \sum_{i=1}^{n} (u_i(E_x))^2 = \sum_{i=1}^{n} (C_i \cdot u(x_i))^2 \tag{6}$$

After identifying the input quantities and their corresponding typical uncertainties, the law of propagation of uncertainties was applied, such that:

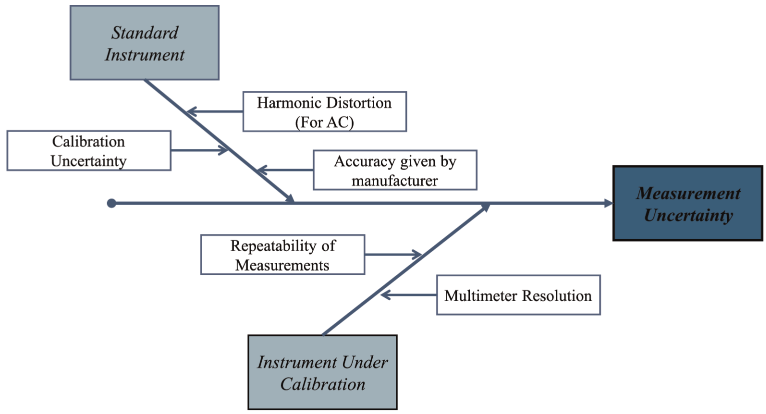


Figure 22.
Representation of process error sources.

$$u_c(E) = \sqrt{\sum_{i=1}^{n} \frac{\partial E^2}{\partial x_i} \cdot u^2(x_i)} \tag{7}$$

where $\frac{\partial E}{\partial x_i}$ corresponds to each of the sensitivity coefficients of the input variables.

Finally, we determine the factor k that ensures a coverage probability of 95.45% in the results, such that the expanded uncertainty can be determined as follows:

$$U_{exp}(E) = k \cdot u_c(E) \tag{8}$$

4.1 Presence of atypical data

From the results obtained by the recognition system, it was determined if there was presence of atypical data, which was done graphically from a box plot. In general, it was evidenced that in the data capture, there was no presence of atypical data, product of the bad recognition of the images, but by the natural behavior of the equipment under calibration. **Figures 23–27** show some of the diagrams obtained at specific calibration points:

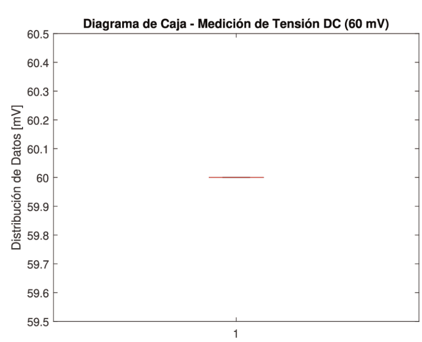


Figure 23.
Box plot 60 mV_{DC}.

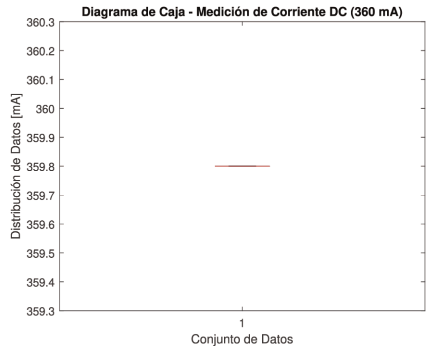


Figure 24.
Box plot 360 mA_{DC}.

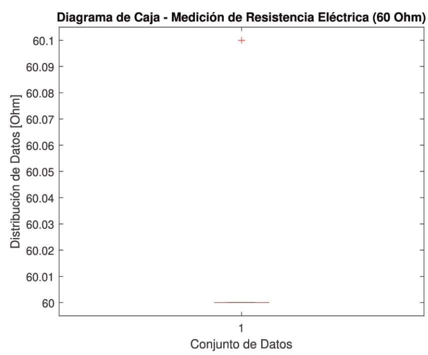


Figure 25.
Box plot 60 Ω.

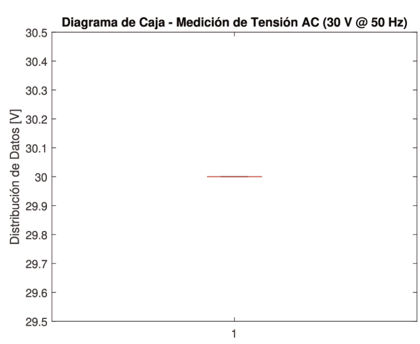


Figure 26.
Box plot 30 V_{AC}.

4.2 Normalized error

The statistic called normalized error, in association with the box plots, was one of the parameters used to evaluate the validity of the results obtained from the calibration performed by the system. To perform the evaluation, the reference and processing system errors and uncertainties are used.

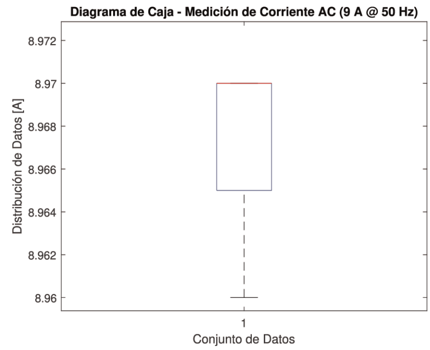


Figure 27.
Box plot 9 A_{AC}.

Nominal value	Test values		Reference values		E_n
	Error	**U_{exp}**	**Error**	**U_{exp}**	
60 mV	0.000 mV	0.058 mV	0.000 mV	0.057 mV	**0.0000**
54 mA	−0.02 mA	0.015 mA	−0.026 mA	0.011 mA	**−0.3217**
6 $k\Omega$	0.0020 $k\Omega$	0.0019 $k\Omega$	0.0000 $k\Omega$	0.0058 $k\Omega$	**−0.3274**
540 V @ 1 kHz	0.2 V	1.1 V	0.56 V	0.41 V	**0.3046**
9 A @ 50 Hz	−0.032 A	0.027 A	−0.030 A	0.033 A	**0.0467**

Table 7.
Error normalizado para funciones de medición.

Table 7 shows some of the results obtained from the *normalized error*.

Given that there is no evidence of outliers produced by the recognition system and that the normalized error values remained in the range of 1 and −1, it is possible to conclude that the system results are satisfactory and therefore, at the metrological level, the system is capable of reporting reliable results.

5. Conclusions

The purpose of this work was to improve the data acquisition system in the calibration of handheld digital multimeters that do not have communication protocols other than their display. Therefore, a system was developed to automatically capture, process, and recognize the values associated with multimeter readings.

In order to achieve this objective, three fundamental subprocesses were developed:

In the first stage, an initial database was created with the multimeter models to work with. The information associated to the required measurement points was related, considering the normative procedure used. Information on the instrument to be calibrated was associated to each of the points, such as ranges and specifications; for the standard instrument, information on the specifications or maximum error allowed by the manufacturer was also related.

In the second stage, an algorithm was developed that, based on the geometry of each segment, identifies and classifies in an ordered way each number of the display of the instrument under calibration. It started with a first trimming of the display with respect to the rest of the image, where a second stage of trimming is then performed where the position of each digit is identified and, based on a count of black and white pixels, it is determined which segments are on or off. With the information obtained, the displayed values are labeled and compared with reference labels to associate numerical values to what is displayed by the acquisition system. From the tests performed, an overall system accuracy (600 samples) of 99.33% was obtained; where, particularly for the Fluke 112, 179, and 87-V models, the percentage of correct recognition was 98.5%, 99.5%, and 100.0%, respectively. As an alternative to mitigate processing errors, a verification process was implemented to discard the processed values whose amplitude is not within the maximum and minimum limits established on the median value of the data vector.

The third stage included the reporting of the results and the metrological assurance of the implemented system. The measurement uncertainties associated with the process were established, taking into account the normative procedure, which, in turn, follows the guidelines of the guide for the expression of uncertainty in measurement [2]. Finally, the quality of the results was evaluated metrologically, comparing them with reference values reported by external suppliers for the same items.

Based on the percentage of successes obtained by the data capture system, the strategies implemented to mitigate processing errors and the proposed metrological evaluation metric, it was determined that the capture and uncertainty estimation system is adequate to perform the calibration process of digital multimeters. In general terms, the automatic data acquisition system for the calibration of digital multimeters through digital image processing has sufficient accuracy and metrological support to perform the calibration process of handheld digital multimeters that do not have a communication protocol that facilitates the automation of the process.

6. Recommendations

For future works related to the presented project, it is recommended to improve the physical compartment and the illumination system since they are highly relevant components to perform a correct task of recognition of the values displayed on the display.

Likewise, it is recommended to strengthen the numerical recognition algorithm to allow a greater variation in the input conditions that affect the process such as illumination, inclination, and distance, among others.

Acknowledgements

This chapter summarizes the published master thesis in Spanish by the same author: Hurtado Castaño [8].

Note

To see the detailed development of the project, please refer to the repository of the Universidad Nacional de Colombia, through the following link: https://repositorio.unal.edu.co/bitstream/handle/unal/82929/1016074514.2022.pdf?sequence=2&isAllowed=y.

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