Virtual Instruments in dimensional metrology

Jesús de Vicente y Oliva
jvo@etsii.upm.es
Universidad Politécnica de Madrid
Spain

Angel María Sánchez Pérez
amsanchez@etsii.upm.es
Universidad Politécnica de Madrid
Spain

Wilmar Hernández Perdomo
whernan@ics.upm.es
Universidad Politécnica de Madrid
Spain

Abstract: *During the last five years, in order to improve understanding of content related to "Coordinate Metrology", the Laboratorio de Metrología y Metrotecnia (LMM) from the Polytechnic University of Madrid offers its PhD students, as a course work, the construction of a virtual instrument. This virtual instrument simulates the imaging of a part to be measured by optical dimensional metrology instruments (microscopes, profile projectors, vision machines). The LMM provides students with images similar to those they would obtain with real instrumentation for the instrument adjustment and calibration process. Working with these images, students should determine the adjustment parameters of the virtual instrument. Once these parameters are set, the student can perform the proper calibration of the virtual instrument. Beyond this process, the instrument is already able to perform traceable measurement. In order to do that, LMM offers students some images of parts. Students should perform some measurements using those images and estimate the corresponding uncertainties.*

Introduction

Professors of the *Laboratorio de Metrología y Metrotecnia* (LMM) from the Polytechnic University of Madrid have been teaching more than 30 years the subject "Dimensional Metrology" in doctorate programs. Currently, this course belongs to the Interuniversity PhD Program "Metrology and Industrial Quality" of the National Distance Education University (UNED) and the Polytechnic University of Madrid (UPM). Also, the LMM is the oldest Spanish laboratory accredited by ENAC (Spanish National Accreditation Board) to perform dimensional calibrations.

During five years, the LMM has offered its students the construction and use of a virtual instrument as course work into the subject "Dimensional Metrology". This instrument is a virtual scanner. The student receive, from the LMM, images corresponding to a real o

simulated scanning of a real part in a real instrument. The student will receive from the LMM such images electronically.

The objective to be achieved is that the student will improve the understanding of whole process of measurement (JCGM, VIM 3rd, 2008):

1. **design** and **construction** of the instrument,
2. **adjustment** of the instrument (VIM 3rd, 2008, 3.11),
3. instrument **calibration** (VIM 3rd, 2008, 2.39),
4. estimation of the **calibration uncertainty** and
5. estimation of **instrumental measurement uncertainty** (VIM 3rd, 2008, 4.24).

Both the chosen instrument (scanner or microscope) and the proposed work plan permit, if student have access to real instrumentation, the repetition of the whole process on a real instrument. In the opposite situation, students can work exclusively with LMM generated images.

Instrument choice

Authors have chosen a commercial scanner capable of obtaining a photographic image of a plane measurand. Figure 1 shows the image of a scale obtained using the commercial scanner shown at the left: a Canon CanoScan LIDE 200. This instrument has a working area of 210 x 297 mm and an optical resolution up to 4800 dpi (dots per inch). Using this device the LMM has generated all the images sent to students.

In fact, it can be used any other optical instrument capable of providing two-dimensional graphic image of a measurand, as it could be a microscope equipped with a digital camera. In practice, the adjustment and calibration techniques presented to students were developed by LMM to be used with microscopes.

The main restriction introduced by the commercial scanner over a microscope or profile projector is that the part to be measured must have all geometry to check on the plane that rests directly on the scanner glass.
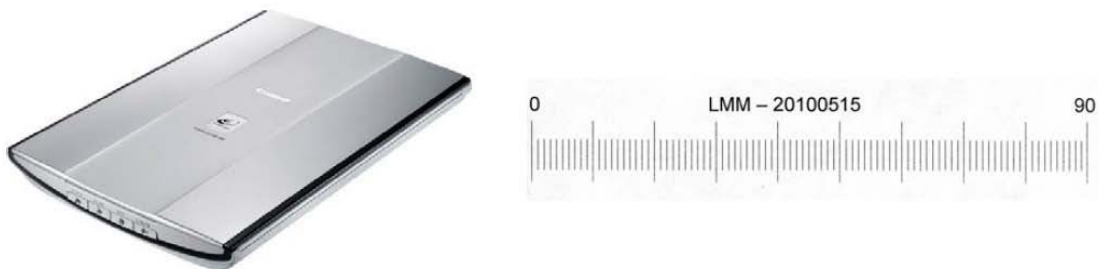

Figure 1: Image of scale obtained with the commercial scanner showed on the left

Two main reasons were taken into account when choosing the commercial scanner:

1. Students with a special interest in this work can repeat the whole process a real instrument: a commercial scanner (this device is an affordable one and easy to use).
2. Also, a commercial scanner has a relatively large measurement range (in an A4 scanner work area is 210 x 297 mm) which allows measurement of macroscopic size pieces. At the same time, it can be calibrated with macroscopic patterns (typically calibrated scales). In both cases, manipulation is easier and in the case of patterns, they can be easily manufactured using an inkjet printer and high quality paper.

Construction of the Instrument

The construction of the measuring instrument consists in writing and implementing a series of computer routines that perform four distinct tasks:

1. **Automatic detection of measurand edges** of and estimation of cartesian coordinates of their points.
2. **Adjusment of geometric elements** (lines, circles, ellipses, arcs or ellipse, etc ...) to the measurand edge points.
3. Determination of **distances and angles** between geometric elements.
4. **Construction of new geometric elements** from the existing ones (eg, a straight line passing through the centers of two circles).

Depending on student's particular interests in the subject "Dimensional Metrology", this part of the work can be directly delivered to the student (as routines written by LMM) or a work in a particular area such as the following can be proposed:

1. Edge detection algorithms.
2. Detection and elimination of outliers.
3. Adjustment of geometric elements.
4. 4. Storing the information in a structured and easily retrievable database.

As an example of LMM routines available to students, Figure 2 shows the result obtained by fitting an ellipse to edge points, automatically detected, corresponding to an elliptical hole. LMM routines include edge detection algorithms and least squares techniques. The red curve represents the fitted ellipse and the blue one represents the residual distances between the edge points and the ellipse (with a x100 amplification). In this example, orthogonal regression techniques were used to make the ellipse adjustment. LMM routines also provide additional information about the correlation between the orthogonal distances. This information can be very useful for those students who want to center their work around uncertainty estimation.

To validate the work done by the student, the LMM has a large number of images of real measurands obtained with optical instruments (scanners, microscopes, etc ...) that can be

sent to student electronically. However, unless the student requests it, images generated by the commercial scanner of figure 1 will be sent be sent to him.
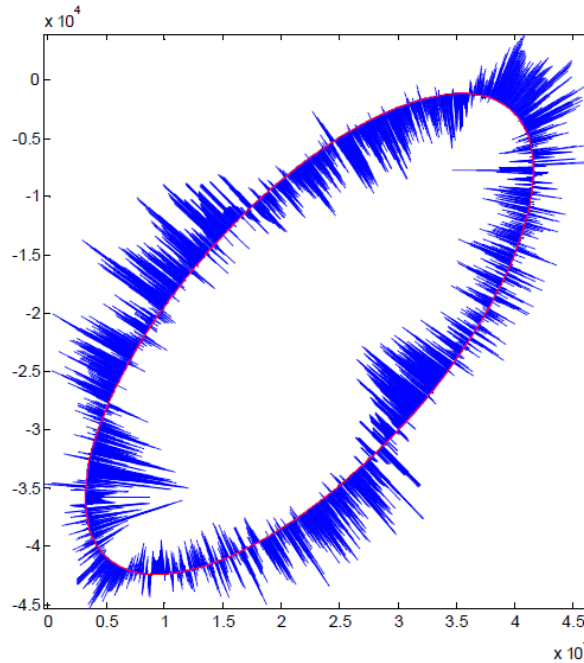

Figure 2: Ellipse adjustment by orthogonal regression (units in μm)

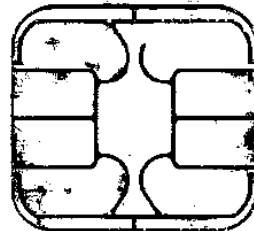## Instrument adjustment

Figure 3a.- Original color image

Figure 3b.- Processed black and white image

Automatic edge detection routines work with black and white images of the measurand. The scanner can directly provide black and white images or, when neccesary, generate grayscale or color images that will be manually adjusted (contrast, brightness, saturation, etc ...) and converted to black and white using standard photo editing software (see figures 3a and 3b). Unless student shows a particular interest in working with color or grayscale images LMM will send him only black and white images.

In any case, edge detection routines work with an array of zeros (dark) and ones (light) in which pixel position is known through the indices i and j of the pixel in the array. The subscript i grows when moving down along the image and the subscript j grows when moving right.

In order to have the pixel position information in x,y Cartesian expressed in units of length (mm) is necessary, in principle, the following:

1. Have an estimation of the horizontal (pX) and vertical (pY) pixel size.
2. Take into account that i,j axes orientation do not match x,y Cartesian axes orientation. Therefore, we have:

$$x = p_X \cdot j \; ; \; y = -p_Y \cdot i$$

Nominal pixel sizes are known when using commercial scanners because before using the device it is necessary to choose its resolution r which is expressed in dots per inch (dpi, dots per inch). Usually, the horizontal and vertical resolutions are equal:

$$p_X \cong p_Y \cong \frac{25.4mm}{r}$$

However, when using an optical microscope (with an attached digital camera) to have an estimation of the pixel size is not so simple. In this case, pixel size depends on camera sensor size, its resolution (megapixels), lenses used, etc ...

Therefore, the best alternative is measuring an object with known sizes, and from the data obtained, determine the horizontal and vertical pixel sizes. This is the alternative that LMM proposes to students.

LMM provide students with images (figure 4) of a square gauge scanned with the commercial scanner of figure 1. The side of the square gauge has nominal lengths equal to 100 mm. Using one of this images, students can measure the horizontal side length L_{PX} of the square and the vertical side length L_{PY}. From these results they can estimate the horizontal (p_X) and vertical (p_Y) pixel sizes:

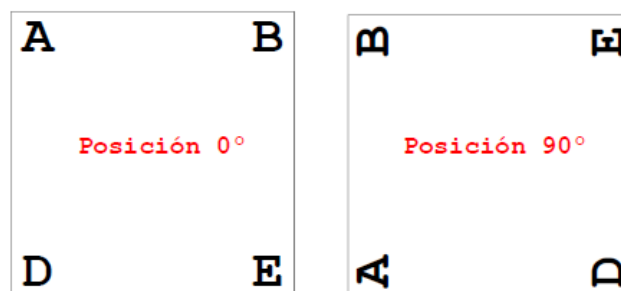$$p_X = \frac{100mm}{L_{PX}} \; ; \; p_Y = \frac{100mm}{L_{PY}}$$

Figure 4: Pattern of adjustment measured at two positions of 90°

If students have a real commercial scanner and want to work directly with it, the LMM can send a PDF document containing the image of the square gauge shown in Figure 4 and they can print it using an inkjet printer on photo quality paper. Working in this way,

student can manufacture its own square gauge and the can perform the whole adjustment process with a real instrument.

If the square gauge is measured in two positions, 0 and 90 degrees (see Figure 4), it can be observed that measured angles corresponding to the vertices A, B, D and E slightly vary from 0º position to 90º position. This is due to the fact that i,j axes may not be exactly perpendicular (see Figure 5), showing a small squareness defect α.
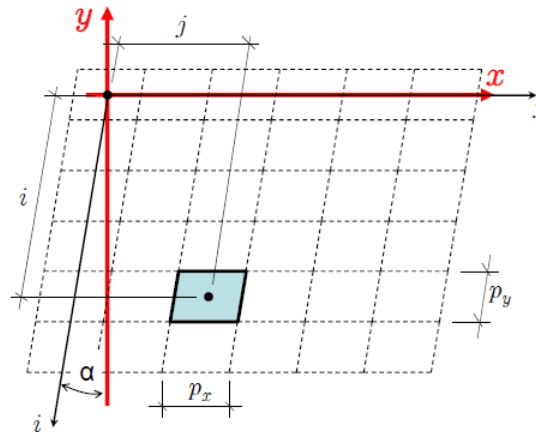

Figure 5: Relation between the cartesian axes x, y and (i, j) axes of the pixels

By measuring angles A, B, D and E in two positions to 90 degrees, it is possible to estimate the squareness defect α of the scanner. An estimation of α can be obtained in absence of a prior knowledge of angles A, B, D and E. It is only necessary that these angles have a real value close to 90 . Once an estimation of α has been obtained, the new equations relating the x,y Cartesian coordinates x, y with i,j indices i, j of the pixels in the array are:

$$x = +j \cdot p_X - i \cdot p_Y sin\alpha \ ; \ \ y = -i \cdot p_Y cos\alpha$$

In this moment, the student has been able to make a complete instrument adjustment. If he uses a virtual scanner, the images he worked with has been provided electronically by the LMM. If he uses a real scanner, the LMM has provided only a PDF file with the square gauge design, he has printed this file on a high quality paper and using it, he has performed the scanner adjustment.

This adjustment process needs a measurement standard (JCGM, VIM 3rd, 2008, 5.1): the square gauge. Therefore, it is not necessary this standard to be calibrated (JCGM, VIM 3rd, 2008, 2.39), remember that the adjustment process has been done using a nominal value of the lengths of the square sides sides (100 mm).

As a result, the x,y cartesian coordinates are still not traceable (JCGM, VIM 3rd, 2008, 2.41), since the scanner indications (JCGM, VIM 3rd, 2008, 4.1) have not been compared against a calibrated length measurement traceable to the unit of length (the meter of the International System of Units, SI). This activity is described in the following section.

Instrument calibration

Once the instrument has been successfully adjusted according with the process described in previous paragraphs, the scanner can be calibrated using a calibration procedure very similar to that used to calibrate profile projectors (CEM, 1999).

To those students who choose to use real scanners, the LMM provides them with traceable measurement standards that have been calibrated with a profile projector. The scale shown in figure 1 was printed on a high quality photographic paper and then attached to a flat metal plate no more than 2 mm thick. This type of scale can be easily made and easily calibrated in a traceable profile projector and ensures good dimensional stability over time.

Students using a virtual instrument receive images from LMM corresponding to the calibration of scanner shown in Figure 1.

Calibration is performed by placing the scale to the scanner X axis first and then parallel to the Y axis. For each axis, eleven distances between scale marks are chosen in such a way that nominal values of these distances cover uniformly the axis range (210 mm for the X axis and 297 mm for the Y axis). The student receives, therefore, two images. An images with the scale parallel to the axis X and the other one with the scale parallel to the Y axis Y. Also, the student receives the calibration certificate of scale issued by LMM.

For each distance, the student must perform ten repetitions of the distance measurement. To perform these measurements the students use the routines listed previously: edge detection routines, adjustment of geometrical elements and estimations of distances between geometrical elements. In order to get different indications in each of 10 repetitions, the working area chosen for each mark of the scale should vary. For example, we start using as working area the tenth top of the mark and in the following repetitions the working are will go down until you will have ten regions of scale mark that cover this mark completely. Sometimes, the LMM has supplied ten scale images obtained moving slightly the scale between one image and the following. In this case, the student should use the full mark to find the distances.

Using the certified values of the scale distances (written in the calibration certificate) and every one of the ten values corresponding to each one of the ten repetitions, the student must determine the calibration correction of the scanner axis for each nominal distance and estimate the corresponding uncertainty according to ISO-GUM guide (JCGM, GUM, 2008) and supplement 1 (JCGM, GUM-S1, 2008), using a procedure analogous to that used in the calibration of profile projectors (CEM, 1999). From these results, it is relatively straightforward to estimate an overall null calibration correction for each axis looking for the point where the sum of the absolute value of the calibration correction and its uncertainty reaches a maximum value.

But for those students with specific interest in the "Coordinate Metrology" and estimation of uncertainties in accordance with new techniques described in ISO-GUM Supplements 1 (JCGM, GUM-S1, 2008) and 2 (JCGM, GUM-S2, 2008), LMM propose them to determine

calibration corrections c_{PX} and c_{PY} for parameters p_X and p_Y described in the previous section, along with their uncertainties accompanied by the correlation coefficient between c_{PX} and c_{PY}. Once this task is done, the new x, y Cartesian coordinates of a pixel can be estimating using the following expressions:

$$x = +j \cdot (p_X + c_{PX}) - i \cdot (p_Y + c_{PY})sin\alpha$$
$$y = -i \cdot (p_Y + c_{PY})cos\alpha$$

Students who choose this way of working should also estimate the uncertainty associated with the evaluation of the squareness defect α.

Measurement

Once the instrument (real or virtual) has been calibrated, it and can be used to do dimensional measurements. In order to minimize the problems related with edge detection in images of workpieces (which are closely related to the reflectivity of the workpiece, the presence of scratches on its surface and contrast, brightness and saturation settings of the scanner) LMM uses only black measurands. The figure below shows some of them:
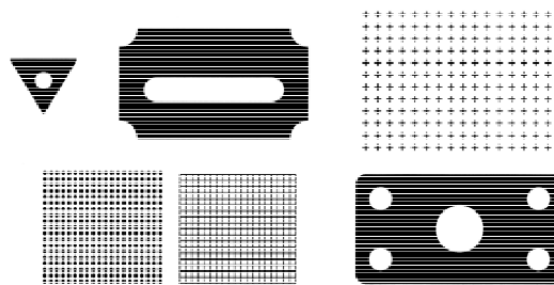

Figure 6: Some measurands provide by LMM to students

On these measurands, students must measure some dimensions. Figure 7 shows the proposed dimensions to be measured in a particular workpiece sent to a student.
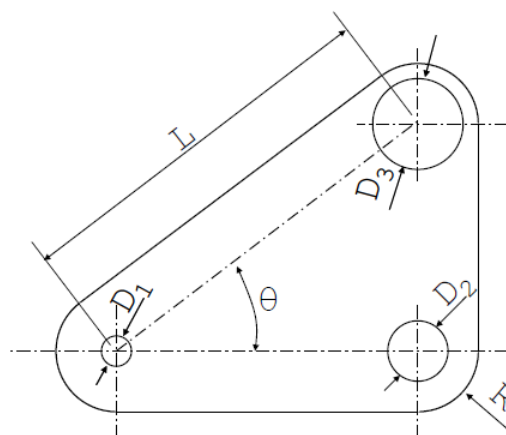

Figure 7: Example of some dimensions proposed to be measured

If the student works with a virtual instrument, the LMM sends him some workpiece images similar to those of figure 6 obtained with the scanner of figure 1. If the student can work with a real scanner, then the LMM will sent a real measurand that has previously been measured in a LMM profile projector (although this measurement data won't be sent to the student). This real measurand must be scanned by students in their scanners and, using the images provided by their instruments, they must perform the measurement asked by LMM. To carry out these measurements the student has access to routines listed in "Construction of the Instrument".

Uncertainty Propagation

In metrology, each measurement result should be accompanied by its corresponding measurement uncertainty (JCGM, VIM 3rd, 2008), and should be estimated according with ISO-GUM guide (JCGM, GUM, 2008) and/or its supplements 1 (JCGM, GUM-S1, 2009) and 2 (JCGM, GUM-S2, 2008). Depending on student interest on the area of uncertainty estimation, different techniques can be proposed to the student in order to get a better uncertainty estimation.

In case of simple measurements, it is possible to apply directly the Law of Propagation of Uncertainty described in the ISO-GUM using a model function where the overall null calibration correction of the scanner is introduced (see section "Instrument Calibration").

In case of complex measurement, it is necessary to use simulation (Monte-Carlo) techniques (JCGM, GUM-S1, 2008) and/or propagation of uncertainty matrices (JCGM, GUM-S2, 2008), see too (Cox y Harris, 2006) and (JCGM, 2009). In these cases, the overall null calibration correction is substituted by calibration corrections c_{PX} and c_{PY} and the squarness defect α which are used in conjunction with a model for coordinate measuring machines developed by LMM (de Vicente y Raya, 1999; de Vicente et al., 2005). Thinking on making the work easier, students are provided by LMM with the necessary routines to propagate uncertainties during the adjustment of simple geometrical elements (circumferences, lines, ellipses, arcs) using Monte-Carlo techniques.
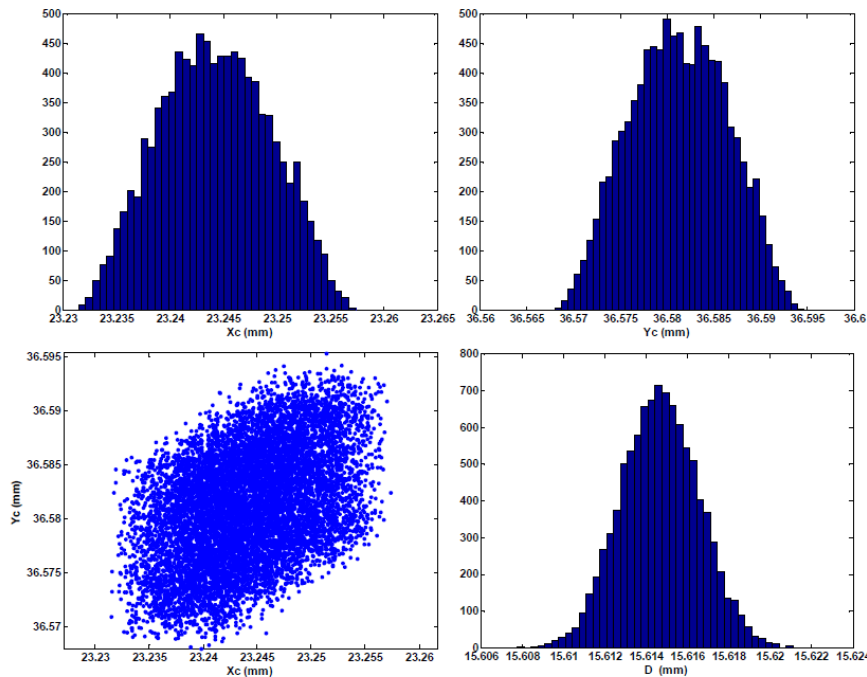
Figure 8: Simulation of a diameter measurement with the scanner of figure 1

Figure 8 shows the results obtained during the estimation of the measurement uncertainty corresponding to measurement of the diameter (15,6 mm) of a circular hole performed with the scanner of figure 1. The measurement results are the Cartesian coordinates x_C , y_C of the center hole and the diameter D. Please note that the uncertainties of the center coordinates are close to 10 μm while the diameter uncertainty is only 5 μm. In figure 8, it can be observed the presence of positive correlation (the correlation coefficient was 0,44) between x_C and y_C . Finally, the histogram of the diameter D simulation shows that the probability density function of the diameter is very close to a normal distribution. On the contrary, x_C and y_C seem to follow distribution functions closer to triangular distributions.

Result Analysis

All measurements proposed to student were previously performed by the LMM with a traditional instrument like a profile projector. Because of that, the LMM have references values z_0 and their corresponding uncertainties $U(z_0)$ for each measurement proponed to students. When a student finished his work, he should send to LMM a measurement result z accompanied by its corresponding uncertainty $U(z)$. From these values, a compatibility index E can be evaluated. This index measure the compatibility between the result provided by the student and that provided by the LMM (the reference value). When the compatibility is high, this index is close o zero. When results are not compatible the index is higher than one:

$$E = \frac{|z - z_0|}{\sqrt{U^2(z) + U^2(z_0)}}$$

This compatibility index is widely used in metrology to analize the compatibility between measurement results, corresponding to the same measurand, provided by different laboratories. If this index is lower than one, the measurement result is considered compatible and it is accepted that the result z and its uncertainty U(z) have been correctly estimated. If you exceed the value of unity, this indicates that problems have arisen either in the estimation of its uncertainty U z (z), which will subsequently be investigated and resolved.

Conclusions

The proposed working method to students, by default, consists in using images generated by the LMM in the scanner of Figure 1 from real measurands. This allows the student to work at home without any completary presential sessions at LMM laboratory, even if he does not have any real instrument. The work under these conditions is performed on an virtual instrument. The proposed work covers the entire metrological process, from instrument construction to final validation of measurement results.

Depending on the particular interest of every student, LMM can offer slightly different works to each student, with some work parts larger or shorter as a function of student interests. Thus, a student interested in the development of edge detection routines in specific applications (eg verification of sieves) will work harder in this area (edge detection) but will use a simplified method of estimation uncertainty. Instead, a student particulary interested in estimation of uncertainties in "Coordinate Metrology" will increase his workload corresponding to the section on "Measurement" but he will decrease the workload corresponding to the section "Construction of the instrument" using the standard routines supplied the LMM.

If the student has a scanner to work with and he wants to measure real measurement standards and workpieces, the LMM can provide him with calibrated measurament standards to be used during the calibration of his real scanner. Finally, he will be able to use his scanner to perform traceable measurements on real workpieces.

Results obtained during last years show that forcing students to confront real and complete problems (even using a virtual instrument) that involves the construction, adjustment, calibration and use of a measuring instrument permits the detection of gaps in student knowledge that otherwise will not be detected. In some cases, these gaps correspond to fundamental concepts such as adjustment and calibration that seemed to be well established but, actually, they were misunderstood by students. As a result, this way of working force the student to rethink and to reflect on these fundamental concepts and, finally, he end up dominating the field.

Also, this work of reflection of the student is very useful when he is preparing his doctoral thesis topic (remember that the subject "Dimensional Metrology" is a doctoral course). This reflection helps to detect weaknesses in his project and to clarify points that initially seemed to be clear but, after a period of deep reflection forced by a work like that described in this paper, some dark areas appear.

References

CEM : *"Procedimiento para la calibración de proyectores de perfiles"*. Proc. DI-001. Centro Español de Metrología. NIPO/ISBN: 165-99-003-4. 1999.

Cox, M. G. ; Harris, P. M. : *"Software Support for Metrology Best Practice Guide No 6 – uncertainty evaluation"*. National Physical Laboratory. DEM-ES 011, September 2006. www.npl.co.uk (accessed on July 1, 2011)

de Vicente, J. Raya, F. : *"Simplified statistical method for uncertainty estimation in coordinate metrology"*. Actas de Metrologie '99. Burdeos.

de Vicente, J. et al. : *"Estimación de incertidumbres mediante propagación de distribuciones en metrología por coordenadas"*. Actas del 3er Congreso Nacional de Metrología, Zaragoza, Mayo de 2005.

JCGM : *"Evaluation of measurement data – Guide to the expression of uncertainty in measurement"*. JCGM 100:2008 (GUM), www.bipm.org (accessed on July 1, 2011)

JCGM : *"Evaluation of measurement data – An introduction to the Guide to the expression of uncertainty in measurement and related documents"*. JCGM 104:2009, www.bipm.org (accessed on July 1, 2011)

JCGM : *"Evaluation of measurement data — Supplement 1 to the Guide to the expression of uncertainty in measurement — Propagation of distributions using a Monte Carlo method"*. JCGM 101:2008 (GUM-S1), www.bipm.org (accessed on July 1, 2011)

JCGM : *"Evaluation of measurement data – Supplement 2 to the Guide to the expression of uncertainty in measurement – Models with any number of output quantities"*, (GUM-S2). ISO/IEC Guide 98-3/Suppl. 2 (2008), www.iso.ch (accessed on July 1, 2011)

JCGM : *"International Vocabulary of Metrology – Basic and General Concepts and Associated Terms"*. VIM, 3rd edition, JCGM 200:2008 (VIM), www.bipm.org (accessed on July 1, 2011)

Acknowledgements

Copyright Statement