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Educational Programme for Virtual Calibration in Dimensional Metrology: Development and Evaluation*

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This article describes the structure and content of educational software, developed with the aim of training engineering students in the calibration of standards and instruments in the field of dimensional metrology. The virtual character of the environment created makes it possible to substitute practising with real metrological equipment for versatile and interactive simulations that provide advantages such as: the reduction in the cost of acquiring and maintaining standards and instruments; the absence of time and space constraints; the provision of training in any metrology condition, and accessibility for students with movement or sensory limitations, etc. The structure of the programme requires the students to engage in active learning. As such, they have to make metrological decisions that ensure traceability and estimate the uncertainties in accordance with the established calibration procedures. A pilot project was carried out with the aim of analysing the teaching viability of the program. This made it possible to objectively evaluate the level of learning reached by mechanical engineering students at the Polytechnic University of Madrid.

Keywords: engineering education; metrology; calibration; virtual learning; educational software

INTRODUCTION

DIMENSIONAL METROLOGY forms part of the higher academic training of engineers on different courses, such as mechanical, aeronautical, naval and civil engineering amongst others, either as a specific subject [1–10], or as part of other subjects such as mechanical technology, manufacturing engineering or quality engineering [11–14]. In addition, some engineering schools have postgraduate courses and masters degrees in metrology [15–17]. There are also higher education centres and institutes of metrology that form part of different universities throughout the world [18–24] dedicated to basic and applied research in this discipline. This situation of pre-eminence has not come about by chance, as the science of metrology is essential to achieve the necessary precision in manufactured products, which are permanently subjected to increasing demands in terms of dimensions. In short, the interchangeability and quality of such products can only be guaranteed when adequate measuring equipment is available which is traceable, that is, is calibrated. With the aim of contributing to this training package, the virtual calibration laboratory (VCL) presented in this article was developed for use in engineering schools.

Virtual environments in university teaching

The emergence of a new teaching role for university lecturers, with increasing emphasis on the processes more than the content of the teaching, shifts their role towards the work of mediating, directing and planning self-tuition strategies. In this way, the interaction in virtual worlds forms an appropriate setting in which to put to the test some of the fundamental postulates of "self-learning". Simulated environments constitute a powerful computing tool, compatible with methodological principles in which interactive teaching and constructivism are based and, without a doubt, its implementation also provides other economic advantages. The existing simulation programs in the area of medical sciences and aerial navigation are widely known [25, 26], and are pioneers of this type of resource. As far as teaching in the engineering schools is concerned, they constitute an ever more widespread tool [27–32]. They are currently even used to a considerable extent in the study of humanities and social sciences at university, disciplines which by nature are more theoretical and are traditionally opposed to the use of virtual environments, [32–35]. In the field of electronic metrology and instrumentation there are papers published which elaborate teaching methodologies for the teaching of measurement systems [36] and the explanation of the concepts of error and uncertainty in measurement [37]. However, in the field of dimensional metrology there are no known references to any type of

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software aimed at the calibration of instruments as presented in this article.

CALIBRATION OF STANDARDS AND INSTRUMENTS

In metrology, the result of the measurement of a magnitude M is expressed as: $M = m \pm u$, where m is the most probable value of the magnitude M and u is the measurement uncertainty. This shows that the true value of the magnitude is found to be between the values ($m–u$, $m + u$) and it is inferred that the uncertainty can be defined as an interval, generally symmetrical, within which the true value of the magnitude measured is found with a determined probability. This definition shows the random character of uncertainty and the convenience of treating it statistically.

The origin of the uncertainty is of a varying nature and depends on the measurement conditions and the characteristics of the instruments, for example: mechanical imperfections, electronic drift, instability in the measuring, thermal variations, etc.

Depending on the method used for its numerical determination, the ISO Guide [38] and the document EA-4/02 [39] establish two groups of sources of uncertainty: those which are estimated through statistical procedures from the values obtained on repeated observations of a measurand (called type "A") and those which are evaluated by other methods (called type "B"). Both types must be quantified by means of variances and, where appropriate, through the corresponding covariances if there are situations of dependency (Fig. 1).

In practice, the above recommendation makes it possible to determine—by application of the law of propagation of variances—the typical combined uncertainty (u) from all the sources considered in a systematic and simple manner:

$$u^2 = u_{A1}^2 + u_{A2}^2 + ... + u_{Ai}^2 + ... + u_{B1}^2 + u_{B2}^2 + ... + u_{Bj}^2 \tag{1}$$

Where:

$u_{Ai}{}^2$ = type "A" i-th variance and

$u_{Bj}{}^2$ = type "B" j-th variance.

The multiplication of u by a coverage factor (k), usually between 2 and 3, makes it possible to obtain some expanded uncertainty values (U) for a determined level of confidence.

Fig. 1. Contributions of type "A" and "B" uncertainties

$$U = k \cdot u \tag{2}$$

The calibration of all standards or instruments is aimed at quantifying their uncertainty following the above recommendations, under certain criteria of a practical nature that depend on the characteristics of the standard or instrument in question and which are set down in the documents called calibration procedures, published by the different national metrology institutes, in Spain the CEM (*Centro Español de Metrología*). The information contained in the procedures offers guidance regarding the way in which each calibration must be carried out. In general, this can be summarized into eight steps:

1. Criteria to use in the selection of the nominal calibration point or points: x_{0i}.
2. The type and characteristics of the standards to use.
3. Determining the combined typical uncertainty of the standards (u_{0i}), when the nominal values are obtained by the addition of two or more.
4. The way in which the measurements on the calibration point or points must be repeated: environmental conditions, stabilisation times, the number of repetitions, the rejection criteria, etc.
5. The model for obtaining type "A" uncertainties. After carrying out n measurements of a standard with a nominal measurement x_0, in repeatability conditions and after obtaining the individual values $q_1, q_2, \ldots q_k, \ldots q_n$, which are assumed to be independent, the statistical estimator *arithmetical mean* (x) is determined as:

$$x = \bar{q} = \frac{\sum_{k=1}^{n} \bar{q}_k}{n} \tag{3}$$

The dispersion of the n results is determined in the first instance by means of the experimental statistical estimator *standard deviation* (s_q) by means of the expression:

$$s_q = \sqrt{\frac{\sum_{k=1}^{n} (q_k - x)^2}{n - 1}} \tag{4}$$

This value would be completely reliable if n were sufficiently large. For common metrological situations this standard deviation is corrected by the application of the central limit theorem, as follows:

$$u_q = \frac{s_q}{\sqrt{n}} \tag{5}$$

6. Determining the calibration correction (c_c):

$$c_c = x_0 - x \tag{6}$$

7. Enumerating the sources of type "B" uncertainty and estimation models for these. The incorporation of these sources of uncertainty is based essentially on metrological experience. The procedures bring together the source of each one of these uncertainties (the scale division, defects in the flatness of the measurement jaws, Abbe error, corrections for temperature, etc.) and the calculation formulae. Generally, the only information available is the extreme distribution values (*a*–, *a*+) and an intuitive knowledge of the behaviour of the variable. Given that the intervals are normally symmetrical, that is to say: $a+ = |a-| = a$, the variability is estimated using the following formulae, according to the type of distribution being considered:

   - Normal: $$u_x = \frac{a}{\sqrt{9}} \quad (7)$$
   - Triangular: $$u_x = \frac{a}{\sqrt{6}} \quad (8)$$
   - Rectangular: $$u_x = \frac{a}{\sqrt{3}} \quad (9)$$
   - U distribution: $$u_x = \frac{a}{\sqrt{2}} \quad (10)$$

8. The equation for calculating the final expression of expanded uncertainty (U): the coverage factor (*k*) to be employed, rounding off criteria, the convenience or inconvenience of incorporating the correction of the calibration as a source of uncertainty, etc.

VIRTUAL CALIBRATION LABORATORY (VCL)

Structure

VCL is software designed to serve as an integrated teaching tool, rather than simply a virtual calibration environment. Formally it is structured into six sections which are represented by the tabs that appear in the main menu: *Start, Tutorial, Notes, Statistics, Help* and *Web* (Fig. 2).

The option 'Start' opens different functions which provide access to the main operations, such as: measure; see the laboratory instruments individually, see these instruments according to the levels diagram, obtain statistical data, etc. The option 'Tutorial' offers the user a guide to operating the programme. To this end, it includes sections such as: presentation, structure of the contents, how to begin the calibrations, examples with solutions, frequently asked questions, etc. The third tab includes, under the general heading 'Notes', different metrological information structured into five large chapters: basic metrological concepts, metrological terminology, classification of dimensional metrology instruments, the calculation of uncertainties and a calibration plan. The option 'Statistics' provides access to all the stored information from one or more users, where data for each instrument are shown, such as: the number of calibrations made manually and automatically, the duration of these calibrations, the number of these that have been completed satisfactorily, the number of times students have accessed help in text format, the number of times students have accessed help in video format, the time spent on each calibration, etc. The 'Help' tab enables the user to make enquiries online by contacting the authors of the software by e-mail. The only requirement stipulated is that the person making the enquiry must have a controlled copy of the software. In order to do this, they must simply indicate in the field reserved for the purpose the number of the copy, which they will find in the documentation that accompanies the VCL installation CD. Finally, the 'Web' tab opens an access page to different internet addresses organised into the following groups: abbreviations and acronyms used in metrology, national standards bodies, metrology research centres, manufactures of metrological equipment, publications on metrology and national metrology institutes.

The concept of virtual calibration

The International Vocabulary of Basic and General Terms in Metrology (VIM) [40] defines calibration as the 'operation establishing the relation between quantity values provided by measurement standards and the corresponding indications of a measuring system, carried out under specified conditions and including evaluation of measurement uncertainty'. The 23rd edition of the *Real Academia Española de la Lengua* (Royal Spanish

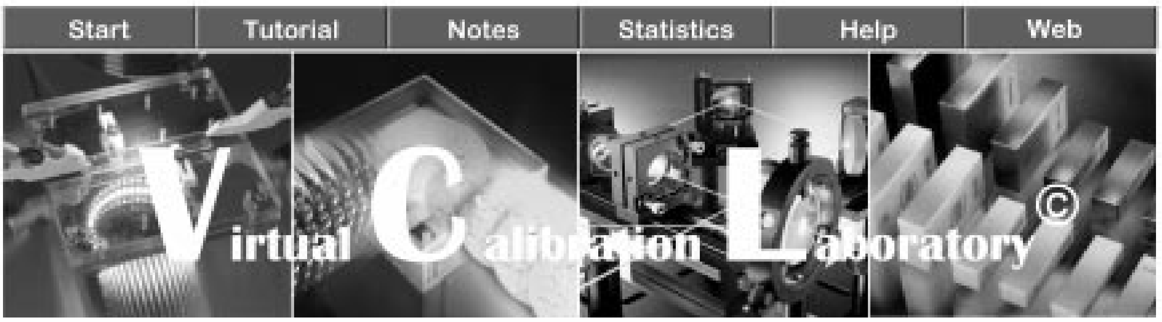

Fig. 2. Tabs on the main menu

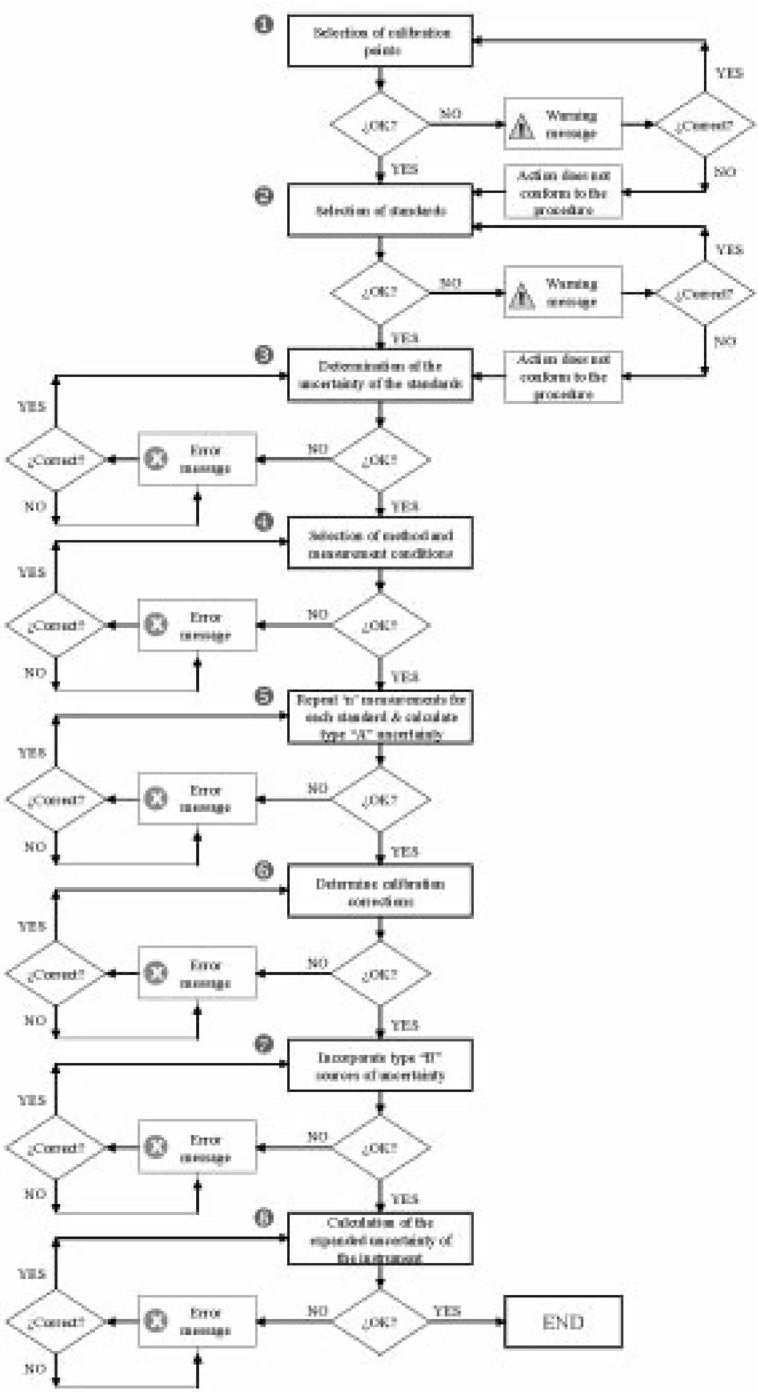

Fig. 3. Calibration flow diagram

Language Academy) (RAE) [41] defines virtual reality as the 'representation of scenes or images of objects, produced by a computer system, which give the impression that they really exist'. The integration of both concepts—calibration and virtual reality—inspired the creation of this simulation program which was conceived as an e-learning[1] tool aimed at the scientific and technological training of the tasks inherent in the whole dimensional calibration process. With this aim, a common structure was created for all the calibrations as shown in the flow diagram (Fig. 3) with the eight steps described above.

Architecture of the calibration program

The VCL is based on a model of sequential qualification for modules (similar to that which is usually used in videogames) structured in different restricted access sections. The architecture of the program is based on the levels diagram (Fig. 4),

[1] For ASTD (American Society of Training and Development) *e-learning* is: "all that which is distributed or supported in electronic format with the explicit aim of learning" [42]

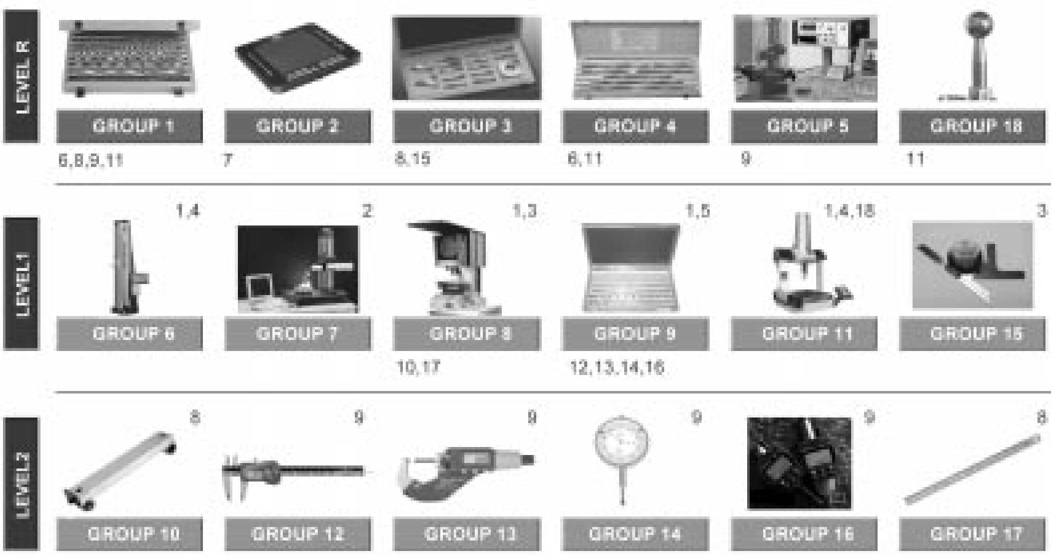

Fig. 4. Levels diagram

which has six groups of standards situated at the reference level (Table 1) and twelve groups of instruments situated at levels 1 and 2 (Tables 2 and 3).

The formation of a group in the levels diagram requires all the instruments in the group to be calibrated with the same groups of standards, using the same general procedures, and their uncertainties being estimated with the same calculation equations. In this case, for simplification, it is considered that there is only one instrument in each group, except in groups 1, 2, 3, 4 and 9 that are formed by sets of standards. Each group has been put at the highest possible level, always below any other used to calibrate it.

Table 1. Level R standards/instruments

Group	Name of standard/instrument
Group 1:	Gauge blocks, grade K, length $\leq$ 0.1 m
Group 2:	Surface roughness standards
Group 3:	Angular gauge blocks
Group 4:	Long gauge blocks, grade 0, length > 0.1 m
Group 5:	Electronic comparator of gauge blocks
Group 18:	Standard sphere

Table 2. Level 1 standards/instruments

Group	Name of the standard/instrument
Group 6:	Vertical measuring machine
Group 7:	Surface roughness measuring
Group 8:	Profile projector
Group 9:	Gauge blocks, grade 1, length $\leq$ 0.1 m
Group 11:	Three-coordinate measurer
Group 15:	Brevel protractor

Table 3. Level 2 instruments

Group	Name of the instrument
Group 10:	Sine bar
Group 12:	Decimal caliper
Group 13:	Exterior micrometer
Group 14:	Analogue comparator
Group 16:	Digital comparator
Group 17:	Line ruler

Calibration procedure

The VCL calibration procedure allows the user a certain degree of autonomy, provided that the user respects the fundamental principle which establishes that any standard or instrument that is going to be used in the calibration of another has been calibrated previously. The hierarchical dependence of the calibration is known beforehand and can be visualized directly on the levels diagram, as the numbers that appear in the lower part of the groups indicate the instruments that each group calibrates, while the numbers that appear in the upper part refer to the groups by which they are calibrated. For example, the exterior micrometer (group 13) is calibrated by the grade 1 longitudinal gauge blocks (GBs) (group 9) which in turn are calibrated by groups 1 and 5 (Fig. 5).

In this case, the calibration of the micrometer will be able to be carried out if the grade 1 GBs have been previously calibrated and these in their turn will only be able to be calibrated if the uncertainties of the grade K GBs (Group 1) and of the bench used for calibration are known.

As occurs in any laboratory, the reference level instruments are calibrated periodically in external laboratories and consequently their uncertainty is known and is of type ‘B’. For example, the models for estimating uncertainty are shown below and some significant screens from the VCL simulation are shown for the calibration of the standards and instruments belonging to groups 9 and 13.

Calibration of group 9 standards

From the recommendations in the CEM calibration procedure [43], the VCL considers seven sources of uncertainty in the calibration of grade

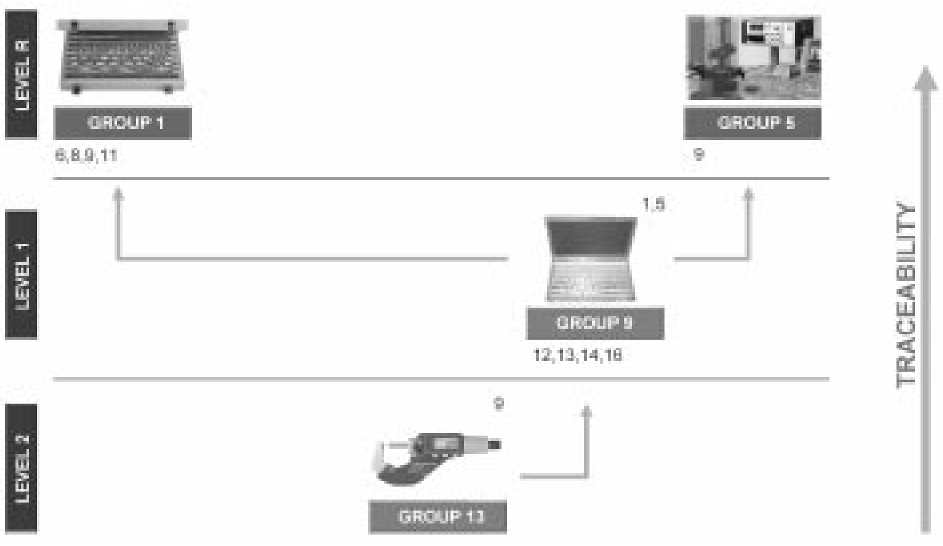

Fig. 5. Diagram of internal traceability of the micrometer

1 gauge blocks of lengths less than or equal to 100 mm (Table 4).

This produces the general expression of combined typical uncertainty *uci:*

$$uci^2 = upi^2 + uDt^2 + uSi^2 + uLc^2 + ut^2 + u\alpha^2 + uLv^2 \quad (11)$$

Where the distinct contributions are estimated as indicated in Table 5:

Finally, the typical combined uncertainty, for each one of the *i* GBs is determined by using the expression:

$$uci = \sqrt{\left(\frac{Upi}{k}\right)^2 + \frac{Dt^2}{3} + \frac{Si^2}{n} + 0.016^2 + (0.058 \cdot \alpha \cdot L)^2 + (0.41 \cdot 10^{-6} \cdot L)^2 + 0.00642^2} \quad (12)$$

Figure 6 shows a instantaneous moment from the help video that is incorporated in the VCL. Figure 7 shows the calibration screen of the grade 1 GBs, after repeating the measurements and carrying out the calculation of expanded uncertainty $U_{(95\%)}$ for a gauge block of a nominal length of 1.004 mm.

Calibration of the instruments in Group 13

Following the recommendations contained in the CEM calibration procedure [44], the VCL considers five sources of uncertainty in the calibration of external micrometers (Table 6).

In this case resulting in the expression of typical combined uncertainty *uci*:

$$uci^2 = upi^2 + uE^2 + uSi^2 + uSm^2 + ucci^2 \quad (13)$$

Where the different distributions are estimated as shown in Table 7.

Finally, the typical combined uncertainty, for each calibration point *i* of the outside metric micrometer results in:

$$uci = \sqrt{\left(\frac{Upi}{k}\right)^2 + 0.289^2 + Si^2\left(\frac{1}{10} + 1\right) + \frac{Cci^2}{9}} \quad (14)$$

The selection screen of the GBs employed in the calibration of the micrometers allows the calibration points to be decided and to carry out, where appropriate, the different compositions to obtain the desired nominal values. It indicates the necessary precautions to avoid incorrect compositions. The application offers, by default, a group of equidistant points along the length of the scale, obtained using the optimum compositions. From this same screen the help videos can be accessed where the cleaning, thermal stabilisation and gauge blocks adherence processes are shown.

Table 4. Sources of uncertainty in the calibration of the GBs

	Symbol	Uncertainty
1	upi	due to the gauge blocks used as reference standards (group 1, level R)
2	uDt	due to the temporal drift of the reference blocks
3	uSi	due to the reading of the blocks' comparator (variability on repeating *n* measurements of the same measurand)
4	uLc	due to the electronic comparator of gauge blocks (group 5, level R)
5	ut	due to the difference in temperature between the reference gauge block and the block that is calibrated
6	uα	due to the difference between expansion coefficients of the reference gauge block and the block being calibrated
7	uLv	due to the variation in length

Table 5. Mathematical expressions of uncertainty in the calibration of the GBs

Uncertainty	Expression	Being	Type
upi	$\frac{Upi}{k}$	*Upi:* expanded uncertainty of each reference GB, for a covering coefficient k = 2	"B" (data)
uDt	$\frac{Dt}{\sqrt{3}}$	*Dt* = ± 0.02 µm + 0.25 · 10^{-6} · L (L: length of the GB expressed in millimetres). The estimate corresponds to a rectangular distribution.	"B" (data)
uSi	$\frac{Si}{\sqrt{n}}$	*Si*: typical sample deviation for a series of n = 10 repeated measurements on the reference gauge blocks, of a nominal value of x_{oi}	"A" (calculated)
uLc	$\frac{ULc}{k}$	*ULc* = ± (30 nm + 0.02 · |D|) D being the maximum difference between the tolerances of the reference gauge blocks and those which are calibrated. Taking d = ±1 μm gives: ULc: 0.032 μm and uLc: 0.016 μm	"B" (constant)
ut	$L \cdot \alpha \cdot \frac{\Delta t}{\sqrt{3}}$	$\alpha = 11.5 \cdot 10^{-6}\ K^{-1}$ (lineal expansion coefficient) Δt : small temperature difference between the reference gauge block and the block that is calibrated. It is estimated as: Δt = ± 0.1 °C *L* : length of the GB, expressed in μm Consequently ut: 0.058 · α · L	"B" (data)
uα	$L \cdot 0,41 \cdot 10^{-6}$	*L* the length of the GB expressed in μm. This contribution represents the typical uncertainty of the mean of expansion coefficients, combining the two rectangular distributions of the difference of the expansion coefficients, assuming the rectangular distribution is within the limits: $\pm(1 \cdot \sqrt{2}) \cdot 10^{-6}\ K^{-1}$	"B" (data)
uLv	$\frac{0,5 \cdot tv}{9 \cdot \sqrt{3}}$	*tv* being the tolerance of variation in length for some grade 1 GBs to be calibrated. Taking for the least favourable case the value: tv = 0.20 μm, uLv = 0.00642 μm.	"B" (constant)

Then the program simulates the measurements reiteration in every calibration point. The interface for data gathering and uncertainties calculation asks for the information that the user must enter. First of all, the differences between the nominal values of the standards and those read from the instrument at each point (*Dij*) must be put in the corresponding boxes. Next, the following calculations must be carried out: the mean of the values for each series (*di*), the typical variation (*Si*), the calibration correction (*Cci*), the combined typical uncertainty (*uci*) according to the equation (14) and the expanded uncertainty (*Ui*) for the coverage factor indicated in the procedure: k = 2. Finally the global uncertainty of the instrument ($U_{95\%}$) is determined, calculated as the greatest of all the *Ui* obtained, and rounded up to a whole number, a multiple of the instrument scale division.

The application also has text help pages in PDF format and videos (Fig. 8) that show the sequence of the metrological operations to be carried out in each case.

THE STOCHASTIC FUNCTION

The necessary variability in the measurements during the calibration process is simulated in this

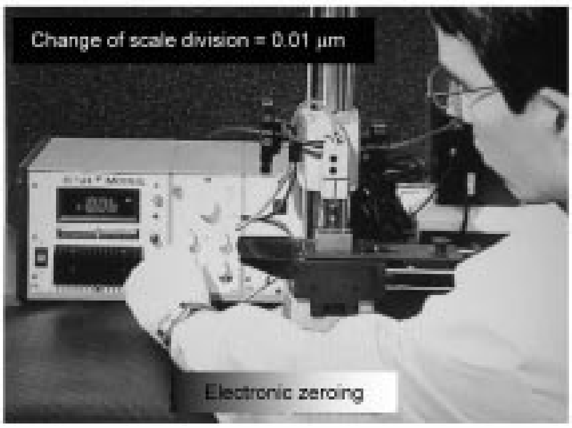

Fig. 6. Scene from the help video

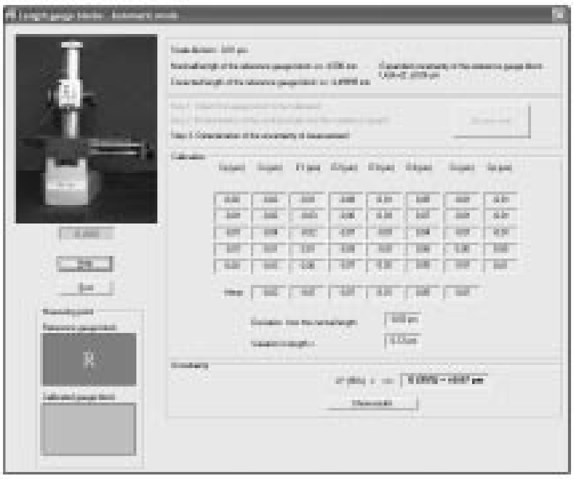

Fig. 7. Screen for the calibration of the grade 1 GBs

Table 6. Sources of uncertainty in calibration of exterior micrometers

	Symbol	Uncertainty
1	upi	due to the longitudinal gauge block or composition employed in the calibration (group 9, level 1)
2	uE	due to the instrument scale division
3	uSi	due to repeatability in the calibration
4	uSm	due to the repeatability in the normal use of the instrument
5	ucci	due to the correction of the calibration

Table 7. Mathematical expressions of uncertainties in calibration of the micrometers

Uncertainty	Expression	Being	Type
upi	$\frac{Upi}{k}$	*Upi* the expanded GB uncertainty (or composition of blocks) employed in the point "i", for a coverage coefficient k = 2.	"B" (data)
uE	$\frac{E}{\sqrt{12}}$	*E* the instrument scale division. In this case E = 1 μm, therefore uE = 0.289 μm	"B" (constant)
uSi	$\frac{Si}{\sqrt{j}}$ $Si^2 = \frac{1}{j-1}\sum_{j=1}^{10}(Dij - di)^2$	*Dij* the differences between the nominal GB value (or composition of the blocks) and the readings of the instrument *di* the mean of the Dij values *j* the number of repeated measurements at each calibration point. In this case j = 10	"A" (is calculated)
uSm	$\frac{Si}{\sqrt{1}}$	*Si* the variability calculated in the previous case. It is considered that Sm takes the same value as Si when one single measurement is made (j = 1)	"B" (data)
ucci	$\frac{Cci}{\sqrt{9}}$	*Cci* the correction of the calibration at point "i"	"A" (is calculated)

program using a simple stochastic function. For this purpose, three possible metrological conditions of the instruments are established which semantically could be defined as: 'good', 'acceptable' and 'deficient'. First, and in a random manner, the program assigns a condition to the instrument to be calibrated. Next, values for the calibration measurements (x_{ij}) are generated within certain intervals as indicated below:

a) An instrument in *good* metrological condition:

$$[(x_{0i} - 2 \cdot E) + c_i] \leq x_{ij} \leq [(x_{0i} + 2 \cdot E) + c_i'] \quad (15)$$

b) An instrument in *acceptable* metrological condition:

$$[(x_{0i} - 4 \cdot E) + c_i] \leq x_{ij} \leq [(x_{0i} + 4 \cdot E) + c_i'] \quad (16)$$

c) An instrument in *deficient* metrological condition:

$$[(x_{0i} - 6 \cdot E) + c_i] \leq x_{ij} \leq [(x_{0i} + 6 \cdot E) + c_i'] \quad (17)$$

Where:

x_{oi}: is the nominal value of the gauge block (or combination of GBs) at the calibration point "i".

E: is the instrument scale division.

c_i: is the correction coefficient, of variable value according to the point on the scale.

c_i': idem.

For example, a metric micrometer (E = 0.001 mm) that is calibrated at a point of nominal value $x_{01} = 10.005\ mm$, whose correction coefficients are $c_i = 2\ \mu m$ and $c_i' = 1\ \mu m$, will be able to give readings with identical probability within the intervals that

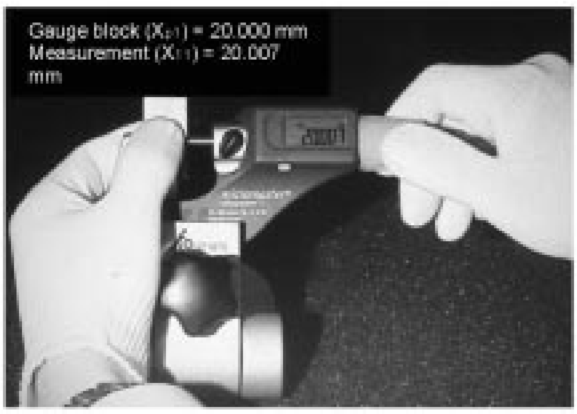

Fig. 8. Scene from the help video

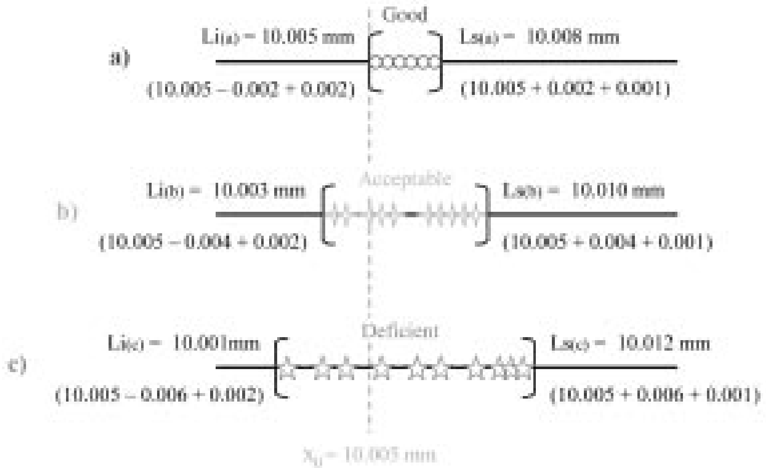

Fig. 9. Graphic representation of the generation intervals of aleatory measurements

are indicated below, according to the metrological condition that the program has selected (Fig. 9):

a) (10.005 , 10.008)
b) (10.003 , 10.010)
c) (10.001 , 10.012)

In this simple way the program carries out the simulation of the metrological condition of the instrument, to determine the values of *ci* and *ci′* and to generate values within the interval obtained for each calibration point.

EVALUATION

With the aim of obtaining objective information regarding the software design, a preliminary evaluation was carried out, related to two different sections, following a commonly accepted model [45]. First, the degree of satisfaction that the students showed after using the VCL, that is, solely the design of the training environment, was evaluated. In addition, the academic results of the students that voluntarily opted to use this virtual environment were evaluated, comparing them with another group of students that did their practical work by attending classes.

Table 8. Statistical data relating to the evaluation of the VCL environment

Item	Question	Number of answers	Mean	Std. Deviation
1	Ease of navigation	12	8.22	0.97
2	Clarity of the content	12	7.71	1.23
3	Structure of the content	12	7.55	1.04
4	Help in text format	12	6.71	1.32
5	Help in video format	12	8.96	0.48
6	Speed of response	12	9.44	0.33
7	Training ability	12	7.69	0.58
8	Flexibility	11	7.88	0.63

Evaluation of the Training Environment

The evaluation of the VCL was carried out using an anonymous questionnaire where the undergraduates had to answer eight very precise questions. This was done after they had used the program for five, two hour sessions, indicating for each question their degree of satisfaction between 1 (very negative) and 10 (excellent). Table 8 shows the mean and the typical deviation obtained for the aspects evaluated.

The data demonstrate a good or very good perception of the software as a whole, as the students evaluated all aspects with a mean score of over 7.5, except for the text format help pages. It is precisely this resource that is the least interactive and intuitive and that requires more effort on the part of the student. Accepting that this aspect of the program received a lower evaluation and, as a consequence, will have to be improved, we suspect that it will be difficult for help in the form of text to be well accepted due to its poor adaptation to a virtual model.

Evaluation of the academic results

This analysis tries to assess the training potential of the VCL. To do so an evaluation was carried out in which the knowledge acquired by the students was estimated by evaluating concepts, skills and aptitudes. In this case the evaluation was carried out by a professor through the observation of the real calibrations made individually by each of the students that had practical training using the VCL. The classifications range from 1 (very negative) to 10 (excellent) for the three areas of evaluation referred to (concepts, skills, aptitudes) and for the three actions analysed. The results obtained are shown in Table 9.

The general results obtained are very good, with an overall average score of 7.9 points compared to 6.5 points obtained by the students who underwent conventional practical training. As would be expected, significantly lower scores in the skills that require manual ability can be seen, an aspect

Table 9. Statistical data for academic results of students using the VCL.

	Selection of standards and determination of their typical combined uncertainty.				Repetition of measurements, data collection and calculation of the statistical estimators				Calculation of the expanded uncertainty of the instrument				
	Score				Score				Score				
Student	C (*)	S (**)	A (***)	Mean	C	S	A	Mean	C	S	A	Mean	Overall mean
1	9.00	6.00	8.00	7.67	8.00	6.00	9.00	7.67	9.00	8.00	9.00	8.67	8.00
2	8.00	5.00	9.00	7.33	9.00	7.00	9.00	8.33	9.50	8.00	9.00	8.83	8.17
3	10.00	7.00	9.00	8.67	8.00	7.00	9.00	8.00	8.00	8.00	9.00	8.33	8.33
4	8.00	7.00	8.00	7.67	7.00	7.00	9.00	7.67	9.50	9.00	9.00	9.17	8.17
5	8.00	6.00	9.00	7.67	9.00	6.00	9.00	8.00	10.00	9.00	10.00	9.67	8.44
6	10.00	6.50	7.00	7.83	8.00	8.00	8.00	8.00	10.00	8.00	10.00	9.33	8.39
7	7.00	6.00	7.00	6.67	9.00	7.00	8.00	8.00	9.50	8.00	10.00	9.17	7.94
8	8.50	7.00	8.00	7.83	6.50	6.00	8.00	6.83	8.00	10.00	8.00	8.67	7.78
9	9.00	6.00	7.00	7.33	7.00	6.00	8.00	7.00	8.00	10.00	8.00	8.67	7.67
10	8.00	7.00	9.00	8.00	8.00	6.00	9.00	7.67	8.00	7.00	7.00	7.33	7.67
11	6.50	6.00	6.00	6.17	7.00	5.00	7.00	6.33	7.50	7.00	7.00	7.17	6.56
12	7.00	7.00	8.00	7.33	8.00	7.00	7.50	7.50	8.00	9.00	8.00	8.33	7.72
Mean	**8.25**	**6.38**	**7.92**	**7.51**	**7.88**	**6.50**	**8.38**	**7.58**	**8.75**	**8.42**	**8.67**	**8.61**	**7.90**

(*) C: concepts, (**) S: skills, (***) A: aptitudes

which cannot be dealt with in an efficient manner in a virtual environment.

CONCLUSIONS

The virtual calibration laboratory (VCL) presented in this paper constitutes a useful and versatile tool for the training of engineers and students on other university degree courses. The user interface developed makes it possible to simulate with a high degree of realism the common activities of all types of calibration, while the levels diagram faithfully reproduces the structure of a real laboratory equipped with eighteen standards and instruments. The program was conceived to provide the student with complete autonomy, while at the same time incorporating the necessary safeguards to prevent them from undertaking incorrect actions. It was also conceived as an independent training tool which offers help in the form of text and video, online advice by means of e-mail, access to web pages and worked examples, constituting an integrated teaching environment for instruction and training in dimensional metrology.

Experiences with undergraduate mechanical engineering students at the Polytechnic University of Madrid have shown a high level of acceptance of the program and some excellent training results in knowledge, skills and aptitudes. On average, scores were 21.5 per cent higher when compared with those of other students using a conventional teaching methodology.

The VCL was developed in a computing format comparable with others commonly used by students on the internet, such as internet games or simulation programs. The active methodology proposed, where the students must make suitable decisions to be able to pass from one level of difficulty to the next, is also comparable to other virtual reality environments such as videogames. All this helps enormously in the use of the software and its acceptance by university students.

The most significant characteristics that make the VCL a highly interesting teaching tool, amongst others, are:

- It makes financial savings possible in relation to acquiring and maintaining costly metrology equipment and eliminates the risks inherent in using such equipment.
- It makes it possible to simulate metrological conditions that would be difficult, if not impossible, to achieve in a real laboratory.
- It makes it possible to simultaneously use as much equipment and as many standards as required, without limitations in terms of either space or time.
- It enables students who have physical or sensory limitations to carry out all types of measurements, including those requiring complex instruments such as three-coordinate machines or profile projectors.
- It enables the incorporation of new standards or instruments as each training centre wishes or requires, as it has a modular structure which is easily adapted.

FUTURE WORK

So far, the formative results with the Virtual Calibration Laboratory program (VCL) have been limited exclusively to students from the Universidad Politécnica de Madrid. In the future we wish to extend the use of this program to other engineering schools in order to test the program in other teaching environments. A new version of the program, adding new standards and dimensional instruments, is expected soon as well as the implementation of an updated and more sophisticated model to generate stochastic values.

The aim for the near future is to add standards and instruments from other metrological areas such as mass, pressure and temperature. In addition, we expect to extend VCL program use to different companies and laboratories, not uniquely to university centres.

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