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Developing virtual instruments in Excel for metrology teaching and training

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Abstract. The use of technology to improve education – either in the classroom or online – is highly positive, making possible to expand the learning experience beyond the classroom or laboratory. In this paper, different technologies are explored focusing in their applicability for metrology training. Then a new approach is proposed, developing different virtual instruments in Excel. This tool allows easy use both for the teacher and the student, is portable between different platforms with a simple file sharing, and is highly applicable to metrology.

1. Introduction

Conducting laboratory experiments is an important part of the learning experience. These activities do not only allow the students to gain practical training; they are essential to visualize how theory works in the real world, get confident about their knowledge, and open their minds to new questions ("what if…?"). However, there are several issues to deal with, such as: time and location constraints, time loses due to the preparation of the equipment, lack of attention of some students when working in groups, limited resources (i.e. quantity of equipment), among others [1].

On the other hand, technology is transforming the education in many ways, providing a variety of tools for teaching/learning, ranging from simple classroom teaching aids to online education. Many problems have been identified concerning the effective implementation of modern distance learning technologies in the university teaching; nevertheless, distance learning through the e-learning courses is becoming the most relevant and widely demanded learning mode over the past decade in higher education [2]. In this context, blended learning (combining personal interaction from traditional class sessions, with online technologies), showed to be more effective in enhancing student learning [3]. In fact, the attention times of the students decline more quickly in the new generations, and often they do not fully appreciate the traditional lessons in the classroom [4].

Then, the use of technology to complement traditional education seems to be a good choice, especially to complement practical training. In fact, many different technology tools were developed through the years, allowing students to perform experiments from a computer, without the need of being physically present at the laboratories: these are called online laboratories.

In this paper, different online education technologies are summarized, and analyzed in regard to its applicability for metrology teaching. Then, specific objectives are posed, in order to select a suitable tool for teaching metrology concepts. Considering those objectives, a new virtual instrument simulation tool – specially designed for metrology teaching - is proposed and developed using an Excel spreadsheet.

1.1. Review: online laboratories

Basically, there are two main types of online laboratories: remote and virtual laboratories. Remote laboratories (RL) use real hardware to conduct real experiments. The control and instrumentation can be accessed through internet, and in most cases monitored in real-time video. On the other hand, virtual laboratories (VL) use simulation software (i.e., there is no real equipment involved). Some of them even feature a 3D environment for a more realistic experience [4].

1.1.1. Remote labs.
The most common array for RL is the two-tiered system. It consists of a lab side and a client side. The lab side is basically a real laboratory with real equipment and hardware. Controls for operating the equipment and sensors to make measures are connected to a computer server, to be accessed online. The client side is the student's computer used to visualize and control the remote lab [5].

Many examples of RL can be found in the bibliography covering a wide variety of applications, most of them related to industrial environments or electronics. Known robust software is used for the equipment-computer interface, such as LabView [5] or SCADA systems [6]. Sometimes, reconfigurable hardware based in FPGAs is used, allowing more flexibility and versatility [7].

The main advantage of RLs is that actual experiments with real equipment are being conducted, but the need of being physically present in the laboratory disappears, eliminating time and space constraints. On the other hand, remote labs have other problems related to costs (equipment and proprietary software), limited access of remote clients, organizational issues regarding the use of the lab from different users [8].

1.1.2. Virtual labs.
Most of these problems can be solved using multimedia tools in order to simulate experiments. There are two main possibilities regarding VL: one is to use commercially available integrated development systems (i.e. LabView, Measurement Studio); another option is developing a custom application, generally using Object-Oriented Programming (i.e. Java applets) [9]. Each alternative have strong and weak points regarding costs, operability, specificity, programming capacities, time-consumption, and versatility, among others.

VLs are a very good choice to complement education and training in metrology, by the use of virtual instruments. Some examples of such applications include: Java applets for simulating dimensional metrology instruments like calipers and micrometers [4, 10], LabView simulation of virtual instrumentation in the field of vibrations[11], and specific developed tools like VIEW (Virtual Instrumentation Workbench for Instrumentation) for electronic instrumentation as a signal generator, a spectrum analyzer and a oscilloscope [12]. Some VLs even have realistic 3D environments and complex simulations covering a variety of experiments [13]. The use of such tools showed to be very positive for the students [14].

An additional use of technology is the use of interactive tools for teaching [15, 16]. They feature interactive multimedia environments to guide the student through the learning process by different lessons and activities. Most of these teaching systems are not actually VL, since there's no possibility to perform experiments.

1.1.3. RLs vs VLs for metrology teaching.
VLs present several advantages over RLs regarding its application to metrology teaching. In the first place, since no real equipment is needed, costs are reduced, there's no space required, and there's no time limitations. Moreover, virtual instruments are usually highly customizable to suit the teaching needs, leading in more versatile systems. In fact, most applications regarding metrology are based on VLs rather than RLs.

Using virtual instrumentation to teach specific topics involves finding a commercial off-the-shelf application that suites your needs, or developing your own. Even with the use of development environments like LabView, programming knowledge is needed. And, in any case, the portability is limited due to the software installation and licensing in the student's computer.

1.2. Motivation and objectives.

The main objective for this work was developing a simple and portable tool for virtual instrument simulation to be applied in metrology teaching, based on the following aspects:

- Simplicity: the tool must be simple, both to the teacher in the develop stage (no programming skills or specific software knowledge required), and to the students in the practice. It should be possible to customize, modify or add new features in a very simple way.
- Portability: the tool should be used in different computers – and even in the cloud – with minimum software requirements, with a simple file transfer. No software installation or licensing should be necessary.
- Specificity: the tool is intended to simulate virtual instruments to teach metrology-related concepts (in particular, applied to electrical metrology) [17]. Thus, it should be capable to simulate different kind of instruments (both digital and analogical), including systematic and random errors.

In this work, a Microsoft Excel spreadsheet was used to simulate different kind of instruments, considering the mentioned aspects could be adequately addressed with the use of that software. Although Excel is not freeware for the general public, Office 365 Education is licensed freely for students and educators [18], and most universities allow students to use special student's licence for Microsoft Office [19]. Another advantage related to the use of Excel is its wide application in metrology laboratories [20], making it a great tool for metrology technicians training.

2. Development of virtual instruments in Excel

2.1. Graphic interface for digital instruments

The design of the graphic user interface is a very relevant part of the project. Attention to the details leads in a more realistic realization and motivates the student to use the tool and learn by playing.

For this implementation, a FLUKE 5522A calibrator and FLUKE 115 digital multimeter images were used. To simulate the LCD displays, the "DJB Get Digital" true type font is used (this font is available online and free for non commercial use). Using any bitmap editing software, the screen of the instrument is painted in a plain color; then, using the "select transparent color" function in the image format tools, the screens renders transparent and allows viewing of the cell value behind the instrument image.
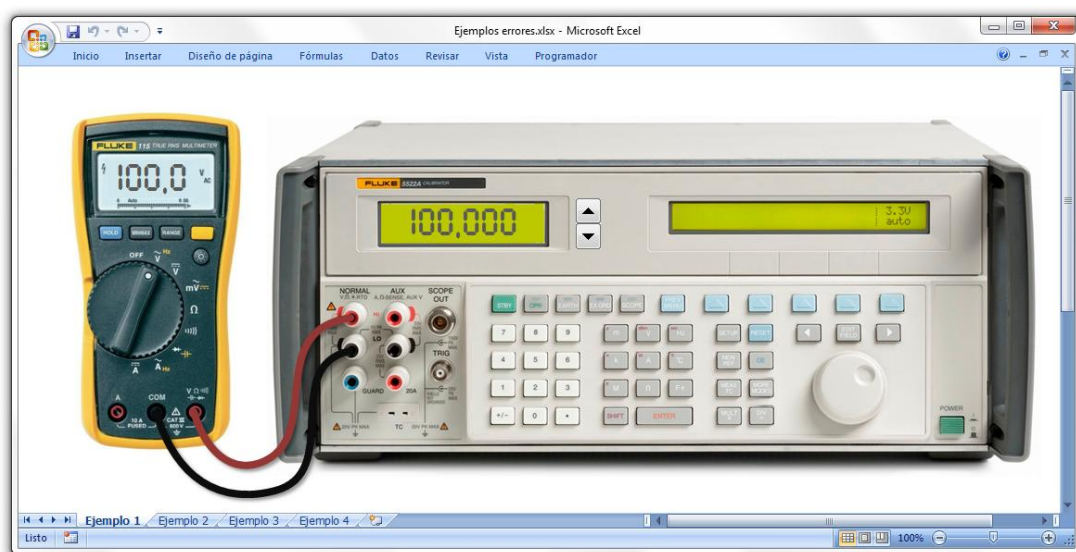

Figure 1. Design of the graphic user interface for digital instruments

Figure 1 shows the final result. Two cells are used for the data: one corresponds to the reference value generated by the calibrator (Vr), and the other to the measured value in the device under test (Vm). A function as simple as Vm = Vr can be used to link both values.

To improve realism, a table can be used to automatically select the resolution for the value shown in the multimeter, simulating the auto range function of the multimeter. Figure 2 shows an example table for a typical 3½ digit multimeter, with ranges being 1,999 – 19,99 – 199,9 – 1000 V (please notice the right way to introduce the values and resolutions in the table). With that table, the following function will give the measured value with the adequate resolution (where *Vm* is the measured value, cell H3 in this case): *=TEXT(Vm;VLOOKUP(Vm;C2:D6;2))*.

Figure 2. Data table to simulate different ranges and resolutions

2.2. Graphic interface for analogic instruments

Developing an analogical instrument interface requires a little more work. The base of the design is an image of the instrument to be simulated (in this case, a 300 V analogical voltmeter).

The pointer is simulated with a line in an XY graphic. The axes are configured from -1 to +1, so the center of the graphic is used as the pointer pivot. The line is drawn using two points: one is always (0, 0) – the pivot – and the other is calculated with a simple formula to point the line in the desired direction – the tip – depending on the measured value.

The graphic is configured with a transparent background, the axes are hide, and the image is positioned besides the graphic, with the pivot corresponding to the (0, 0) point of the graphic. In this case, a small freeform was added in front of the graphic in order to hide the pivoting part of the line and make it look more realistic. Also, the shadow effect is applied to the line.

Figure 3 shows the final result for the analogical voltmeter. As in the first case, one cell is used to input the reference value (Vr), and other cell is used for the measured value (Vm). This cell is hidden from the students, so they can only read the measured value from the instrument scale.
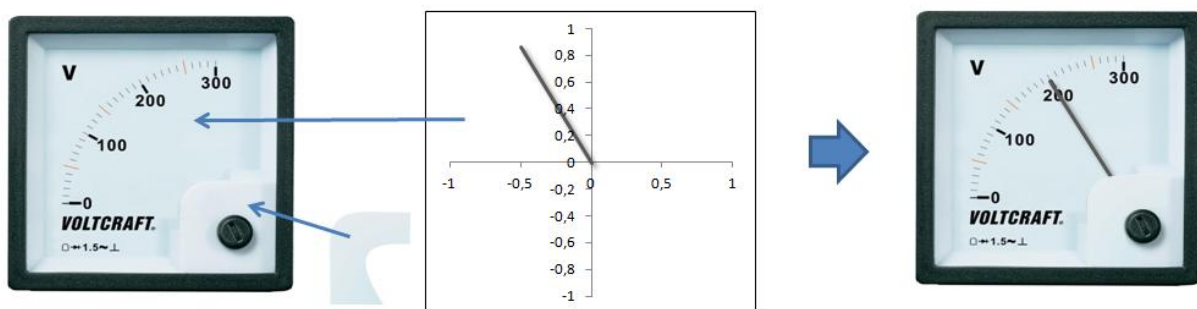

Figure 3. Graphic interface for analogical instruments showing its parts

2.3. Simulating different types of errors

In an ideal instrument, measured value should be exactly the reference value (Vm = Vr). Nevertheless, real instruments (including standard instruments, like the calibrator) have errors that can be simulated in Excel. Different errors can be simulated and then added to the reference value Vr and/or to the measured value Vm. For an easier use of the spreadsheet, it is convenient that every type of error is calculated in a different cell, and finally added altogether to the reference and/or measured value.

2.3.1. Bias. Also called zero error, represents a constant error throughout the scale. It just adds to the measured value; for example, let *ErrZ* be the magnitude of the bias, then: *Vm = Vr + ErrZ*.

2.3.2. Span error. Represents a constant *relative* error throughout the scale, meaning that the absolute error increases (or decreases) along with the measured value. Let *ErrS* be the magnitude of the span error expressed as relative to the measured value, then: *Vm = Vr · (1 + ErrS)* for positive gain error.

2.3.3. Precision error. The lack of repeatability of the instrument can be simulated with the *random* function in Excel. Let *ErrP* be the maximum absolute precision error, then: *Vm = Vr + RAND(-ErrP; ErrP)*. This value changes every time the user enters a value in any cell.

2.3.4. Linearity error. To simulate non-linear responses of the instrument, a polynomial can be used. A very simple way is to choose some error values along the scale, and use the polynomial curve fitting to get the coefficients. For example, the next graph shows an instrument with errors of 0,05 at 40% of the scale and 0,1 at 100% of the scale:
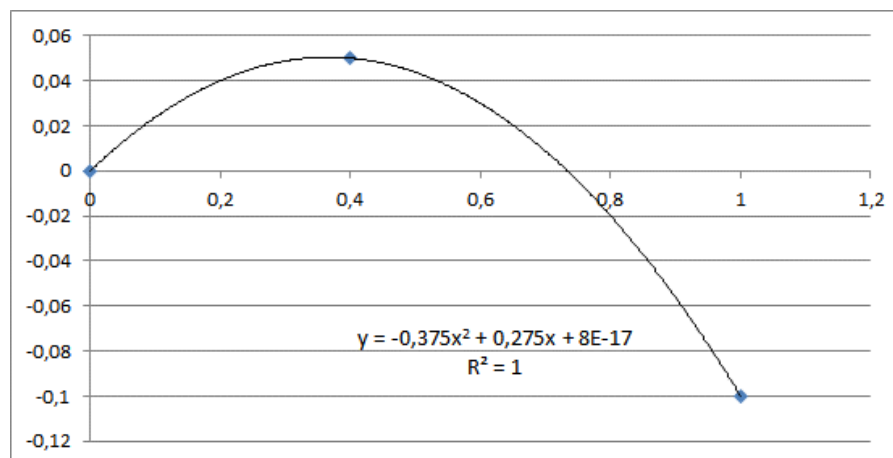

Figure 4. Simulating non-linear response of the instrument

Using the fitting coefficients, the measured value results in *Vm = -0,375*Vr^2 + 0,275*Vr* (the last term can be neglected, since we don't need an exact fit in this case).

Other option is to use known polynomials to simulate specific instruments or sensors, like platinum resistance thermometers (PRT) [21], thermocouples, and others, depending the application.

2.4. Simulating zero-span adjustments

Some instruments – like temperature controllers and other industrial controllers – feature zero and span adjustments. This can be easily simulated in Excel, and is very useful to teach how to configure such devices in order to minimize measurement errors.

Figure 5 shows a virtual temperature controller. In addition to the Vm cell, two more cells are used to input *zero* and *span* coefficients. Usually, in this instruments the *zero* value is added to the measured value, while the *span* value is multiplied by the measured value; then: *Vm = span · Vm' + zero*.

Figure 5. Simulating zero and span adjustments in a temperature controller

3. Proposed activities using virtual instruments

Once the instruments are ready, several activities can be developed to teach different concepts about metrology. Here are some examples. This activities are being used to teach metrology in different courses at the Universidad Tecnológica Nacional, Facultad Regional Santa Fe. The virtual instruments used in this work are freely available on request to the corresponding author.

3.1. Calibration

Using the set up shown in Figure 1, a virtual calibration of a digital instrument can be performed. With this activity, several important metrology concepts can be addressed (accuracy, precision, trueness, systematic and random errors, corrections).

First, an Excel workbook is arranged with 2 or more sheets, each one containing a set up as shown in Figure 1. Each virtual multimeter is configured with different combination of errors as explained in 2.3. Figure 6 shows examples of 2 multimeter responses configured for this activity.
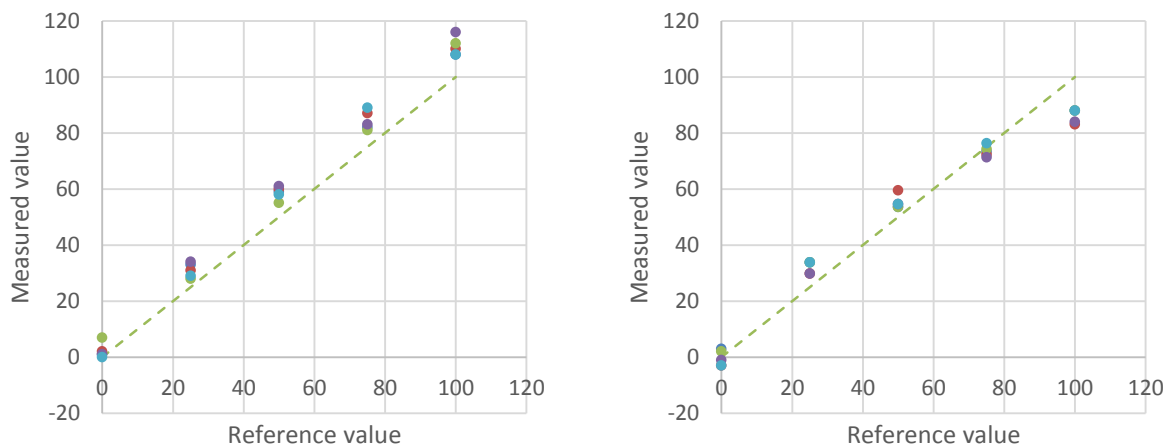

Figure 6. Two multimeter response examples: left: zero + span + repeatability errors; right: linearity + repeatability errors.

Then the students are asked to perform whatever they need in order to identify the different errors of the instruments and determine their magnitude (*they are supposed to perform a calibration, repeating each point several times to estimate repeatability*). Also they are asked to determine the *corrections* that must be applied to each instrument to compensate systematic errors, and check their conclusions simulating other values and applying the corrections. Since the random errors are still present, the concept of *uncertainty* can also be addressed in this activity.

When training personnel of a laboratory having a quality system (i.e. IEC 17015 [22]), part of the training may consist of making a calibration certificate, including the uncertainty estimation.

3.2. Adjustment

Using the set up shown in Figure 5, it is possible to train students to perform zero and gain adjustments in industrial controllers. Previously, the instrument is configured with known bias and span error. For additional difficulty, also a small repeatability error can be configured.

In this activity the students are asked to find the best set of gain and span coefficients, apply them to the virtual instrument, and check their results with additional simulations. Of course, the first step is to perform a calibration as stated in 3.1.

3.3. Interlaboratory comparisons

This activity is useful to address concepts like metrological compatibility, Z-score, interlaboratory comparison, and several statistical concepts. In this case, several different Excel files must be prepared; the device under test must be the same in all of them (it is supposed to be the *traveling standard*), but the instrument used as standard for each student or group (i.e. the calibrator) can vary. In fact, for didactic purposes, some of the standard instruments are configured intentionally with larger errors.

Then the students are told to do perform a calibration at specific points and inform their results, including an estimation of the measurement uncertainty. Finally, all the results are compiled and processed as in a real proficiency test, and the results are analyzed together in the class.

4. Conclusions

The use of virtual instruments to teach metrology concepts to students is very useful, and many concepts can be addressed with the aid of this tool, reinforcing their assimilation by incorporating simulated physical environments. The students are attracted to perform this kind of activities, since they can do *virtual* hands-on experiences without the risk of damaging real expensive equipment. Also, the possibility to customize specific scenarios help the teacher to show particular concepts (for example different types of errors).

In particular, Excel has many advantages over other systems:

- It is very easy to set up different kind of instruments, and customize their behaviour according to the didactic needs. No programming is needed, everything is done with the aid of a few simple Excel functions. Also, systems with a good visual appearance can be achieved.
- If a more complex behaviour is required, further development can be done using Visual Basic for Applications. In this case, although is more complex, the possibilities are virtually unlimited.
- It is very simple to distribute and use, since only a file transfer is needed. It can be used even in a smart phone and with online applications, thus no expensive licenses are required. It makes these virtual instruments especially useful for on-line courses, or when a *virtual campus* is available.

Of course, real experience in a laboratory cannot be fully replaced with the use of virtual instruments, but this results in an excellent complementation for students, since they can perform as many experiments as they need, not being limited in time or location.

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