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IT Innovative Practices in Secondary Schools: Remote Experiments

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Acquisition of higher-order experimental skills through remote and virtual laboratories

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1. **Introduction**

Remote laboratories are physical spaces with real apparatus and real instruments connected to the Internet. They allow both students and teachers to remotely conduct real experiments through a simple web browser. Aktan *et al.* [1] first described the concept of remote experimentation in 1996, and since then many other authors have converged on the idea that remote labs play a significant role in the acquisition of experimental skills if successfully combined with real, hands-on laboratories and virtual laboratories [2-6]. More recently, Feisel and Rosa [7] clarified the sort of experimental skills associated with laboratories. In this paper, Feisel and Rosa describe thirteen fundamental objectives of engineering instructional laboratories, serving as a guide when considering the sort of skills students should acquire after running a particular experiment in a real, virtual or remote laboratory. In the case of a remote experiment, if the provider is able to clearly identify the learning outcomes and the skill gained, then it is possible for a student successfully completing such a remote experiment to acknowledge having acquired the associated skill. This is especially relevant if one considers the following scenario:

1. There is a lack of experimental facilities in secondary schools that impairs students from acquiring experimental skills that are relevant for the fields of Science, Technology and Engineering. This causes students to exhibit a lack of such skills in those fields when entering Higher Education (HE).
2. Increasingly less time is being devoted to lab classes in HE due to: (i) the Bologna process; (ii) cost savings associated with labs, which represent a major cost component in institutions of HE; (iii) an increased use of virtual labs (i.e. simulations), as these imply lower costs when compared to real laboratories.
3. Although simulators represent a powerful and flexible technology-enhanced learning tool, they fail to allow students to interact with Nature, as they interact with mathematical, computer-based models instead. This is a flaw in the educational plan for scientists and engineers who need to be fluent in the language of Nature. Students become fluent in this language by doing and repeating many experiments, where the trick seems to reside not in interpreting the answers obtained from Nature, but rather on asking the right questions so as to better understand the answers obtained [8].
4. Remote labs imply interacting with real apparatus and real instruments. This means that, despite being computer-mediated, the experiments provide results dictated by the nature of such instruments and apparatus under experimentation.
5. The two previous points allow one to think about a sort of higher-order experimental skill associated with the ability to distinguish whether the results obtained from a given experiment clearly allow one to distinguish if one is in the presence of a virtual or a remote lab, in a situation much similar to that proposed by Alan Turing, in 1950 [9].
6. In a scenario where education seems to be shifting from traditional classrooms to everyday-everywhere situations, for instance when accessing Massive Open Online Courses (MOOCs) [10], one is led to think that students may acquire several skills which may be difficult to recognize by traditional HE institutions. In fact, some of those skills may also be related to experiments or laboratory-based materials and procedures [11].

Such a scenario implies the need to promote and recognize the acquisition of experimental skills through informal and non-formal learning activities, such as those acquired through remote and virtual labs [12]. If students and teachers are able to mutually recognize such skills or competences, then personalized experimental learning paths may become a reality in HE, thus allowing students to become fluent in the language of Nature, following their own reasoning and learning pace. Finally, the use of haptic devices may form part of the whole picture, in particular when mentioning experimental skills involving hand-controlled movements or the need for tactile feedback.

This chapter, therefore, addresses the acquisition of higher-order experimental skills through online experimentation. Section 2 discusses aspects related to tagging informal learning activities carried out with online laboratories; section 3 describes the acquisition process in correlation with the fundamental objectives of engineering instructional laboratories (stated in [7]); section 4 focuses on online experiments involving sensorial information; and, finally, section 5 concludes the chapter.

2. **Tagging informal learning activities with remote and virtual labs**

Given the background, it is possible to perceive situations where, by completing a given virtual or remote experiment available on the web, individuals are able to tag an informal learning activity and associate a gained skill with it. The question resides in how to tag that activity and provide evidence of actually having done it. This is particularly relevant with remote experiments –as opposed to virtual ones– because, depending on the nature (resolution, influence of noise, etc.) of the data returned from the lab, results are likely to be unique.

Taking an example from informal learning activities promoted under an initiative named STEM (Science, Technology, Engineering and Maths) Scouts [13], young individuals first (1) study online a given subject, following a recommendation by a teacher or mentor. They then (2) buy an experimental kit to practice the associated practical component (build a scale model, perform a given chemical experiment, etc.) and finally (3) demonstrate the result to the teacher or mentor, who (4) recommends individuals for a STEM Scout badge. Individuals may then (5) add the badge gained to their STEM Scouts electronic portfolio.

Tagging informal activities executed in remote laboratories and adding them to an e-portfolio may follow a similar process, with the exception that no teachers or mentors are involved in it. The main requirement resides in the need for all experiments performed in the remote laboratory to be permanently stored in an associated, Internet accessible and searchable open database containing the following information:

- who did the experiment (requires registration and login credentials): <user id>
- which experiment[1] was done: <experiment id>
- when the experiment was performed: <timestamp>
- what the experiment input parameters & output results were: <experiment setup & results>

Additionally, the remote laboratory should also contain information about the pedagogical framework associated with each supported experiment, i.e. what the experiment is about, the prerequisites, the learning outcomes, etc. Tagging a remote experiment thus simply requires two (optionally, three) actions, namely:

1. Transferring the unique URL identifier of the remote experiment pedagogical contents to an Informal Learning Collector (ILC);
2. Transferring the unique URL identifier of the remote experiment execution data to the ILC;
3. (Optional) Inserting an image illustrating the remote experiment interface to facilitate the reader's comprehension.

A remote laboratory under development which is addressing these specifications, namely by supporting the database with the identified items (who, which, when, what), is described in [14]. The remote laboratory in question allows an individual to perform projectile launch experiments with a number of user-configurable parameters, which enable different pedagogical scenarios, all having in common the physics laws that rule the trajectory of a falling object with a variable launch speed. Fig. 1 provides an overview of the remote laboratory, and Fig. 2 illustrates the user interface, where the elements that will form one record entry of the database are depicted in detail.

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[1] A remote laboratory may host a number of different experiments.

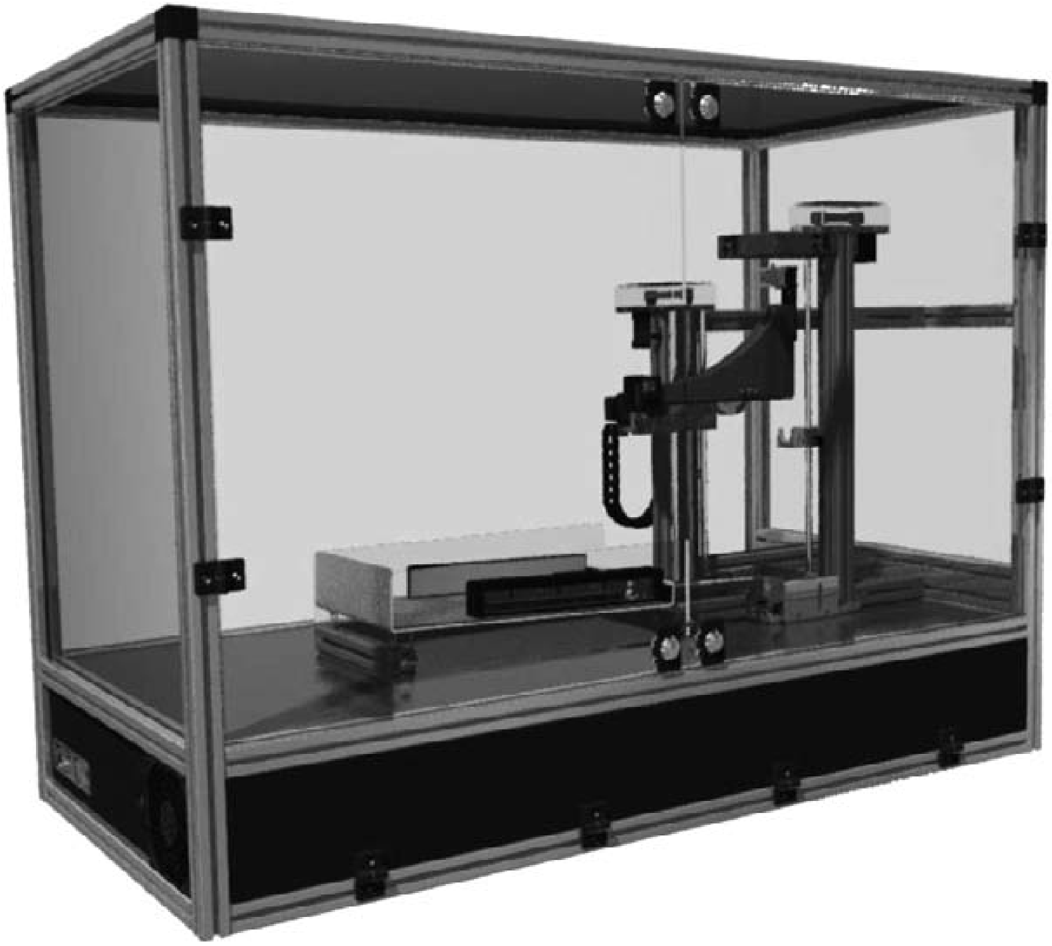

Figure 1

Overview of the physical apparatus for remote projectile launch experiments

A fundamental aspect to be considered is the sort of higher-order experimental skills students may acquire with such a remote experiment. In the presented example (projectile launch experiments), it is possible, for instance, to define a set of didactical problems leading students to navigate through the several "tasks" (or learning scenarios) depicted in Fig. 3. Each learning scenario (pen and paper exercises, online simulations and online lab experiments), and the different (sequence of) transitions among them, is able to provide students with different skills and knowledge. A higher-order experimental skill, in light of Fig. 3, would be the ability to predict and explain the differences among the results provided by each learning scenario, in particular between (online) simulations and (online) lab experiments, as already mentioned in point 5.

The requested resource does not exist or is not available at the moment.

Figure 2

User interface depicting the elements forming a database entry

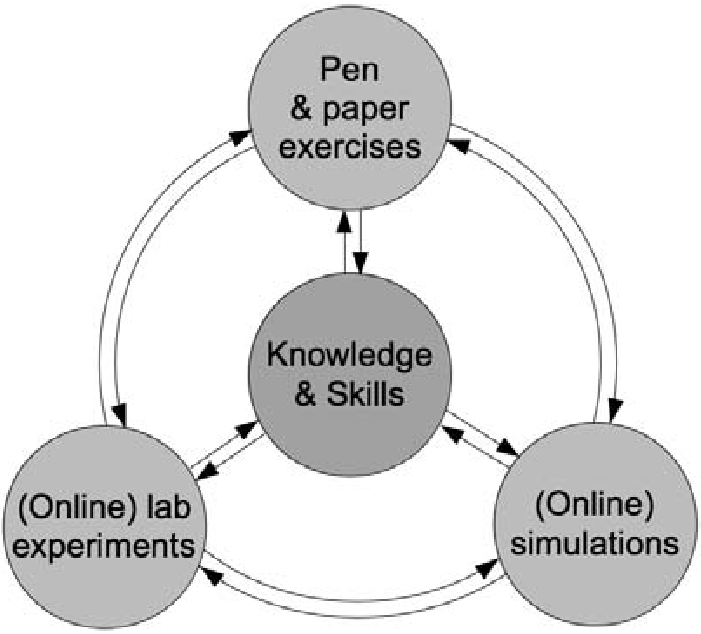

Figure 3

Learning scenarios for acquiring knowledge and skills in Science, Technology and Engineering

3. Attaining higher-order experimental skills with online experimentation

By the mid-eighties computers had been introduced in engineering labs for research, training and education. It is in this context that one of the authors built her own acquisition system for intelligent automated tests of stepper motor driven valves in open and closed loop working mode [15], in order to evaluate their design and performance which were, at the time, under development at the Mechanical Engineering Department of the Faculty of Engineering at the University of Porto. And just for fun it is interesting to remember that a BBC microcomputer was used and its 6502 microprocessor was programmed using assembly language [16]. By the beginning of the nineties, LabVIEW was already in use in universities and in engineering labs [17-22]. Therefore, the computer became everyday laboratory equipment everywhere either to process, analyze and evaluate results' correlation and finally to present them, or to acquire experimental data and to control experiments at research [17-22] or at educational levels [23-26].

LabVIEW and H-P HPVEE software became able to communicate with instruments by using the IEEE 488 communication protocol, which can be looked at as a first standard approach for remote access to the equipment. In the late nineties, LabVIEW and MatLab/Simulink software packages incorporated web server functionalities allowing users to gain remote access to experiments through the Internet [27], and since then many works reported initial activities in the learning context [28-34]. This has been a big step soon after the evolution of the meaning of distance learning education [35], bringing a priceless contribution by providing remote access to experiments within the distance learning process.

However, when ABET had to deal with the accreditation of distance learning education courses, mainly for those at undergraduate level, it was considered essential to establish a clear criterion for defining the role of experimental activities [7]. A group of "some fifty distinguished engineering educators, representing a range of institutions and disciplines" were called to study this perspective, and finally they "converged on a list of thirteen objectives, each consisting of a one-or two-word title to provide easy reference and a brief explanatory statement to help clarify the meaning" [7].

Hoping to add some more material for discussing these topics, in the following paragraphs two case studies will be presented with provocative statements.

A. *The case of hands-on vs. remote experiments*

Using two different solutions as a basis (one being an example of hands-on activity and the other its remote version), a case study will be worked out in order to check how they accomplish these thirteen objectives. This case study integrates one example of complementary instructional resources, with the remote experience being an additional offer to the students' traditional hands-on activities. The selected examples come from the Instrumentation for Measurement course in a Mechanical Engineering integrated MSc. The work is entitled Mechanical Material Characterization, and is related to concepts such as material strain, stress, deformation, Young Modulus, specimen geometry characteristics and bending tests.

Next, a brief description of the activities offered will be given. And, following that, the analysis of the identified outcomes will evaluate what is expected from each solution.

A.1 YOUNG MODULUS DETERMINATION

Hands-on activity

During the hands-on activity a very simple system for obtaining the Young Modulus of a material is used. It consists of a specimen used in a simple cantilever beam mounting (Fig. 4). The specimen is instrumented with two resistance strain gauges oriented along its longitudinal axis and symmetrically bonded on the top and bottom surfaces respectively. The electrical strain gauges are integrated in a half bridge circuit. Known loads are successively applied on the free end of the cantilever beam, at a distance L from the geometric centre of the strain gauges' grid, and for each applied load the strain is calculated based on the signal output of the bridge circuit, the respective load value and the beam geometry dimensions [36]. A regulated and stabilized power supply, a voltmeter and a bridge circuit are the equipment required.

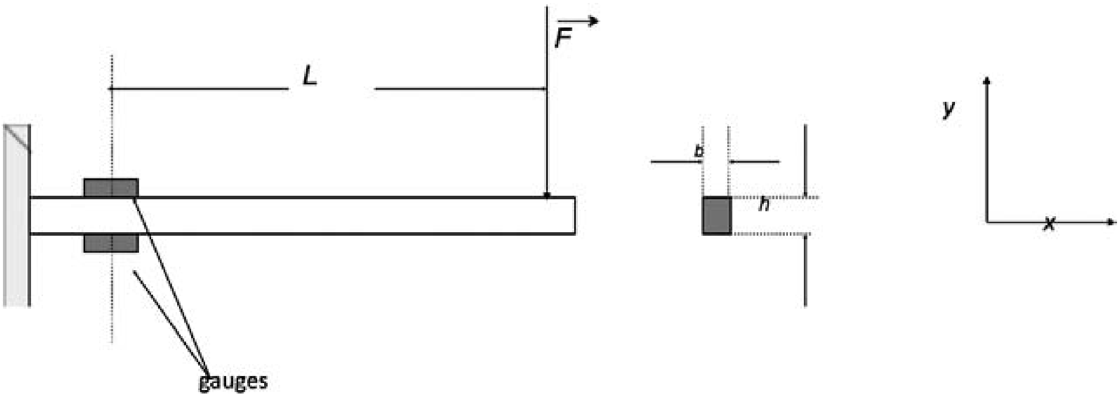

Figure 4

Cantilever beam mounting

Remote experiment (named Mechanical Material Characterization)

The set-up was designed in order to provide the built-in end of the cantilever aluminium beam with a properly tight and stable grip (otherwise, fixed end conditions will not be ensured and relative sliding may occur), as well as the accurate positioning of the motor coil shaft for point load application. The beam is vertically positioned to minimize self-weight effects during measurements. The beam is loaded by a linear motor of coil type in a closed loop control in order to guarantee the load value imposed by a voltage source. A miniature load cell located in serial mounting with the motor shaft provides the reaction force of the beam under load conditions. The strain is measured by electrical strain gauges mounted in a half bridge circuit with a two-wire current transmission circuit. A digital gauge continually gives the deflection of the beam (referred to as the applied load point) for any applied load.

The user interface (UI) is developed in LabVIEW and the acquisition hardware is from National Instruments. The UI is organized into three areas. The main area offers the input actions, either in automatic or manual mode. In both modes, output data is displayed either in graphical or in numerical form, as well as additional information such as test stages, stabilized state, measured values. In the top right-hand corner the system real time video is provided. Below it, a picture of the complete mechanical system is available (Fig. 5), [37].

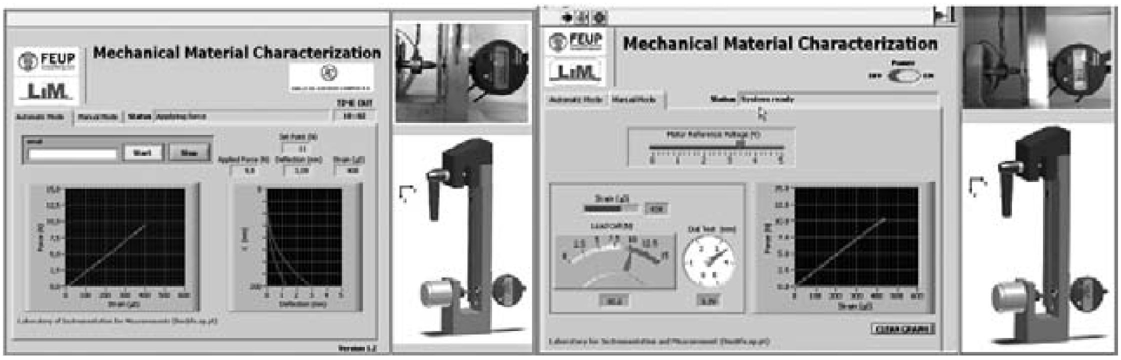

Figure 5

Cantilever beam mounting

Looking at the way the above works were conceived, according to [36], an attempt will now be made to examine how their outcomes accomplish the set of thirteen objectives collected bellow. The first five of them are within the cognition domain; the next two within the psychomotor domain; and the last six are within the affective domain, according to Bloom's Taxonomies [38]. Later discussions on these had by members of the expert group of engineering educators [7] have pointed out a general agreement among engineer educators on the "thirteen objectives'" exhaustive characteristics and their relevance for designing lab courses to aid the evaluation of lab activity and its effectiveness validation, even in distance learning courses. In this context, these objectives will be now considered and, for each experiment, the achievements obtained will be listed in order to evaluate whether there is a clear difference between the two available experimental activities: hands-on and remote.

Objective 1:

Instrumentation: Apply appropriate sensors, instrumentation and/or software tools to make measurements of physical quantities.

- Hands-on: 1) electrical strain gauges are sensors for measuring strains; 2) strain gauges must be integrated into bridge measuring circuits; 3) power supplies need to be of adequate range, regulated and stabilized; 4) measurement accuracy is improved by using some typical measuring techniques and an adequate voltmeter.

- Remote: 1) & 2) similar; 3) loads are applied by a specific controlled device; 4) a miniature ring-type load cell in series with motor shaft is used for guaranteeing load values; 5) the use of some typical measuring techniques and adequate data acquisition resolution improve measurement accuracy; 6) deflection at a specific point is measured by a digital gauge; 7) acquisition cards are essential for obtaining analogue and digital inputs and outputs of and from the system; 8) measurement resolution is defined by analogue/digital converter resolution.

Objective 2:

Models: Identify the strengths and limitations of theoretical models as predictors of real-world behaviors. This may include evaluating whether a theory adequately describes a physical event and establishing or validating a relationship between measured data and underlying physical principles.

- Hands-on: 1) the experiment needs to follow a specific protocol for this type of test in order to obtain results for expressing Hooke's law in the elastic region; 2) accuracy in dimensional values is very important for the result; 3) good results are expected; 4) Young Modulus value is highly dependent on material production.
- Remote: 1) to 4) are similar; 5) if the protocol is not respected using stabilized conditions in the manual mode, measurement will lead to affected results; 6) the use of the available deflection value leads to a less correct Young Modulus value due to second order approximations of the model.

Objective 3:

Experiment: Devise an experimental approach, specify appropriate equipment and procedures, implement these procedures, and interpret the resulting data to characterize an engineering material, component or system.

- Hands-on: 1) the model is based on a cantilever beam under bending test; 2) determination of Young Modulus of a material is based on the slope value of its stress-strain curve in the elastic deformation region; 3) the experiment needs to follow a specific protocol for this type of test in order to obtain results for expressing Hooke's law in the elastic region; 4) the use of spread sheets is advised for performing calculations; 5) the selection of convenient scales is important.

- Remote: 1) to 4) are similar; 5) the system makes it possible to obtain values and to visualize the deflection along the beam; 6) using manual interactive mode and it being possible to have a fine load adjustment, it produces evidence of measurement errors due to a very small strain resulting from small applied loads; 7) if the available deflection value is used to calculate the Young Modulus, a less correct value will be attained.

Objective 4:

Data Analysis: Demonstrate the ability to collect, analyze and interpret data, and to form and support conclusions. Make order of magnitude judgments and use measurement unit systems and conversions.

- Hands-on: the Young's Modulus calculation is highly sensitive to the geometric evaluation of the specimen. This has to be done with some values being of the order of 10^{-5}m! Mistakes and incorrect units will substantially distort the order of magnitude, which is within a well-known value.
- Remote: same type of data; 1) specimen dimensions, loads and strains are automatically provided in the "automatic mode" for analyzes and calculations; 2) by using "manual interaction mode" without respecting the protocol carefully, it will provide good examples of obtaining clear mistakes and allow the exploration of mistakes also coming from applying very small loads; 3) the use of the deformation value will lead to less acceptable results, which will make the influence of the model used evident.

Objective 5:

Design: Design, build or assemble a part, product or system, including using specific methodologies, equipment or materials; meeting client *requirements; developing system specifications from requirements; testing and debugging a prototype, system or process using appropriate tools to satisfy requirements.*

- Hands-on: 1) the test framework has to be assembled – errors in the assembling process will lead to bad results; 2) wrong electrical connections will invalidate results; 3) procedure for nulling offset is mandatory for the final results; 4) scale selection.
- Remote: 1) user interaction and its observation will encourage the student to idealize a much more complex solution to gain remote access to the same type of experiment, therefore contributing to concept integration; 2) wrong functioning observed needs to be identified and reported to the responsible element.

Objective 6:

Learn from failure: Identify unsuccessful outcomes due to faulty equipment, parts, code, construction, process or design, and then re-engineer effective solutions.

- Hands-on: sensing integration, powering and connections could be wrong. If so, results will be affected. The situation should be identified and a solution found.
- Remote: sensing integration, powering and connections could be wrong. If so, given the different types of results provided, the evaluation of those that may be affected should be made. The situation should be identified and reported.

Objective 7:

Creativity: Demonstrate appropriate levels of independent thought, creativity and capability in real-world problem solving.

- Hands-on: it is usually recommended to build a scale based on the instrumented beam. Added open questions are also available in order to force the reflection.
- Remote: available explorations are mainly concentrated when using the manual mode.

Objective 8:

Psycho-motor: Demonstrate competence in selection, modification and operation of appropriate engineering tools and resources.

- Hands-on: this experience implies a hands-on activity to assemble the whole system, the electrical circuitry implementation and connections, as well as the correct application of loads, which involves specific requirements.
- Remote: not applicable presently. However, it is possible to suggest a set of easy experiments to be worked on by the user at home.

Objective 9:

Safety: Identify health safety and environmental issues related to technological processes and activities, and deal with them responsibly.

- Hands-on and Remote: Not applicable in either case!

Objective 10:

Communication: Communicate effectively about laboratory work with a specific audience, both orally and in writing, at levels ranging from executive summaries to comprehensive technical reports.

- Hands-on: Groups involved in an experimental activity have to produce oral reports on their findings for all other groups in the lab. A very short report (a synthesis) is asked for. The performance of the group is also based on these elements. A final experimental test will place all students face to face with teachers in which situation they should execute a randomly selected task; they also have to answer questions related to the topic.
- Remote: group activity is still possible either during the remote access or for results discussion, mainly based on using different approaches. Syntheses of this work are frequently asked for in the final exam or during a lab exam.

Objective 11:

Teamwork: Work effectively in teams, including structuring individual and joint accountability; assign roles, responsibilities and tasks; monitor progress; meet deadlines; and integrate individual contributions into a final deliverable.

– Hands-on: work in a group for the experimental tasks, for the final oral report and to later produce the short and realistic report.
– Remote: considering this work is offered as an additional resource, its evaluation is performed, currently, in the written exam. In the past, online experimentation has been a topic for a poster assessment component. An interesting example of student involvement is reported in [37].

Objective 12:

Ethics in the Laboratory: Behave with highest ethical standards, including reporting information objectively and interacting with integrity.

– Hands-on: group and individual continuous evaluations foster accountability between group elements. Final experimental exam has a mandatory self-evaluation step.
– Remote: when questions are included in an exam, the explanation has to be objectively given. It will not be possible to do this without having performed real access to the experiment or without having used it and explored it. It will foster responsibility in self-regulation of his/her activities.

Objective 13:

Sensory Awareness: Use the human senses to gather information and to make sound engineering judgments in formulating conclusions about real-world problems.

– Hands-on and Remote: Not yet explored.

The first five objectives are rich in content and it is possible to conclude that this remote experiment expands the content even more. Objectives 6 and 7 also have a reasonable balance. However, objective 8 is not respected by the remote solution, according to its inherent remote condition but future steps could integrate improvements in this perspective. Objective 9 is very specific and is not applicable to many lab experiments. Objectives 10, 11 and 12 are balanced and objective 13 has not yet been explored in either situation.

This reflection shows that, in general, most of the objectives are observed in these two versions of the Young Modulus work, which means that both accomplish these important guidelines. Looking in more detail, it is possible to see that, except for objective 9, which is not suitable for many of the lab experiments, and for objective 13, which will be explored for both modalities in the future, all the objectives are fulfilled. Furthermore, in general, it is possible to conclude that the remote version even offers more content for the objectives related to the cognition domain.

Finally, it is possible to argue that with the exploratory interaction possibilities offered, the added training offered with the remote solution will contribute towards "attaining higher-order experimental skills with online experimentation".

B. *The case of remote vs. virtual experiment*

A remote experiment uses real equipment from a physical laboratory, enhanced by software application and technology, connected by the Internet, whereas a virtual experiment is a software application simulating experimental procedures and devices. It can be remotely accessed or even downloaded to the user computer. These concepts are easily available in [39, 40]. A virtual experiment could be just a 2D simulation implemented in Macromedia Flash. But it could also be considerably more complex, using a set of techniques making it possible to interact with a 3D virtual reality (only existing in the computer world). In the "true" virtual reality concept, user perception will use mainly eyes, ears and hands and his/her immersion in the virtual world could reach a high level of realism. The focus will be on virtual reality systems of screen-based simulator type. In this case if virtual reality involves software applications or even techniques which replicate real environments with such a high level of realism that fosters user immersion, then it can lead the user to a higher cognition level compared to when considering a real system.

The case study used for illustrating such an example will analyze a remote experiment of a Michelson Interferometer and its virtual replica. A brief description of both systems will be followed by a comparison of the user actions and feedback they provided.

Basically, a Michelson Interferometer (MI) has different components: a laser, lens, mirrors and one beam splitter. When the laser is on, it generates a monochromatic light beam. A beam splitter, if angled at 45° to the laser beam, is used for splitting it into two beams at the same point in space; one half of the beam intensity is partially refracted through the beam splitter and the other half will be reflected at an angle of 90°. These two half beams will travel along different optical paths and each one will reach the surface of a mirror (one being a fixed mirror and the other a moving mirror). Both will be reflected and they will merge together and combine to produce interference fringes visible when reaching a screen. A diverging lens receiving this final beam before the screen can be used to magnify the interference fringes on the screen. Every time the moving mirror changes its position the optical path will change and this will cause successive light and dark fringes. The fringes will be sliding from bright to dark. For moving mirror changes in position (at the meter magnitude) the fringes will shift. Moving the mirror in the opposite direction will shift the fringes in the opposite direction, too. This system is very interesting not only for viewing and understanding the phenomenon but also because it is the basis of the standard for measuring displacements at micrometer level in metrological labs. In industry it is also relevant in many areas. For example, the calibrator equipment for machine tools is based on the MI working principle. However, an MI is not a common set-up in labs these days because it involves costly equipment, needs to be in a dark room, is very sensitive to any kind of vibration and requires patient and expert tuning. For all these reasons, an MI was prepared to be online. Mechanical interfaces were carefully designed and produced, a special anti-vibrating table was used, a screen was sensorised and a remote application was developed to make it remotely available any time.

STATUS e-mail sent sucessfully

email: trestivo@fe.up.pt

Nominal Speed
- ● Slow (160 nm/s)
- ○ Medium (800 nm/s)
- ○ Fast (4000 nm/s)

20 s - Time interval

Nominal Displacement (mm): 0.00320

Counter: 11

Time (s): 19.91

Displacement (mm): 0.00348

Figure 6

Remote Michelson Interferometer

The user interface offers the interaction area with the available selectable parameters and outputs of numeric and graphical type. In the upper right corner the live video shows the fringes on the screen and how they follow the imposed displacement. In the lower right corner a picture of the complete set-up is shown in Fig. 6.

There are two modes of actuating the interferometer: manual and automatic. In the automatic mode it is possible to choose the velocity for the sliding stage of the moving mirror and the time interval for this movement. These two parameters will impose the displacement. It is possible to introduce the user e-mail to obtain the results (number of fringes, time interval of the displacement) and work with them in order to determine the final real displacement. It is possible to follow the succession of dark/light fringes in the graphical window. In the manual mode, the user can move the sliding stage forwards and backwards, step by step with the resolution of 30 nanometres. This is a great possibility for users.

However, any other action over the system will involve the integration of additional sophisticated equipment and would make it very expensive. For overcoming these limitations a virtual MI (Fig. 7) was built and it is available from http://onlinelab.fe.up.pt/otherexperiments.html

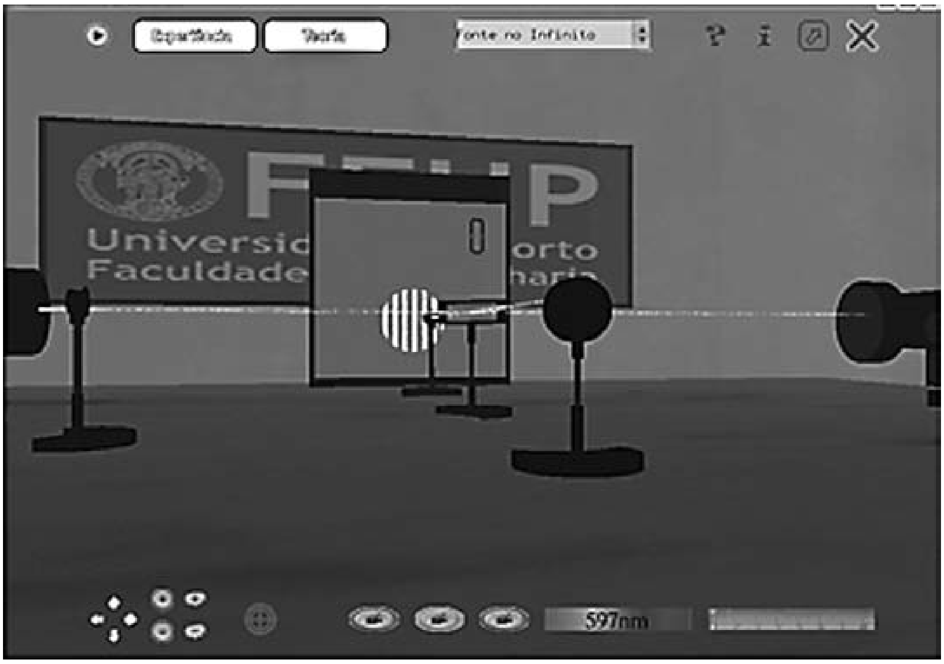

Figure 7

Virtual Michelson Interferometer

The software application can be downloaded easily. A video clip and a tutorial will allow anyone to operate the system and then to explore all its details.

The Virtual MI, Fig. 7, intends to recreate the real interferometer installed in a small, dedicated room. It is essential to switch off the room light and to switch on the laser so that the user can select the laser light beam colour. After making the light sufficiently visible by using some commands, the system can be explored by rotating the scene 360° for the three different cameras. Having decided which camera perspective to use, the next step will be how to tune the beam splitter either using an analogue dial or a fine tuning key for adjusting it at 45° to the direction of the laser beam. The lens near the screen makes it possible to magnify or shrink the fringe pattern. Simultaneously, by clicking on it, the user activates the control slider and, by using this, can observe how its movement produces changes in the fringe's pattern. It is also possible to decide the source type: by selecting a "point source", the fringe pattern will be of circular type and, by selecting "source at infinite", the fringe pattern will be of parallel fringes. By clicking on the sliding mirror, an analogue dial control is activated, whose rotation moves the sliding mirror backwards and forwards. Based on these possibilities, many types of interaction are possible to explore the MI in a richer way and so it encourages the users to become involved and feel confident with the system.

By using all these commands, the user can actuate them and observe the different component functionalities and the MI working principle.

In the present example, students are not allowed to enter the small room where the MI is mounted, so as to avoid any type of interaction with such a sensitive system to any slight misalignments which would immediately make its use impossible. In the present case they can remotely interact much more "safely" than in the lab. Yet, their interaction with the virtual replica is richer and leads to a better understanding of how the whole system works and the role of each component, contributing towards "attaining higher-order experimental skills with online experimentation". The examples visited in the previous sections A and B show that remote and virtual experiments, used in a complementary way, can also contribute to higher-order experimental skills even with their condition of being online experimentation. More complex virtual reality, one offering the user the perception of different types of sensorial information derived from his/her interaction with the virtual world by using kinaesthetic systems, will also contribute to attaining higher-order experimental skills with online experimentation.

4. **Online experimentation involving sensorial information**

Today, simulation software has been produced to accurately provide virtual replicas of many systems as well as processes in all areas of knowledge. In particular, those in technical and physical areas have been playing an important role in engineering education over the last 30 years. User actions on virtual reality systems may involve the perception of different types of sensorial information such as reaction to the action performed in the virtual world. Therefore, the user needs to face kinaesthetic systems, better known as haptic devices. Virtual reality and haptic interaction is another promising area, mainly due to the increase of user immersion within applications for training purposes either in industrial or medical areas. It may be noticed that virtual reality and haptic interaction are inevitably linked to the development of flight simulators. During the second half of the 20th century the universal systems for training pilots for the most sophisticated aircraft before real flights were developed.

Historically, the use of technology to simulate physical phenomena probably found its first serious use in the "Link Trainer" developed by Ed Link in the 1928, now considered an ASME National Landmark" [7]. Interesting videos of the Link Trainer are available at YouTube (http://www.youtube.com/watch?v=fKYyWS9Yfr0 and http://www.youtube.com/watch?v=MEKkVg9NqGM). The pilot inside the "Link Trainer" experienced the sensation of an actual flight experimenting high immersion and it "was used to train thousands of military aviators before and during World War II, saving millions of dollars and more than a few lives" [7].

In recent decades, with the development of IT and of high-resolution graphics, high-speed computer processing, high-speed communications, at the same time as a diversity of interaction devices (haptics, glasses, helmets, gloves, eye-tracking systems, sound), Virtual Reality became a new key technology in use in many fields and to be explored in many others. Virtual reality and haptic interaction, after pilot sophisticated aircraft simulators, have also been used in the Navy for ship or submarine piloting and for training emergency situations (a fire on board, an incident on a submarine, etc.) [41], and for ROV guiding [42], for operating sophisticated equipment at CERN, and for training in nuclear power plants [43] and in complex chemical processes [44], etc. The engineering education areas in which haptic interfaces could be relevant are those based on simulations or virtual reality applications offering the user the possibility of applying and/or responding to the force feedback information to or from the system, and using touch through haptic technology as a powerful tool in computer-based education. However, the cost of those devices is high and dissemination of haptics has not been so extensive. Nevertheless, reported works show a broad range of uses, from traditional dynamic systems where a low-cost haptic of 1DOF was used to interact with an unlimited number of *virtual systems*... "By adjusting the magnitude of the virtual spring constant (Kp) or the virtual damping constant (K_n), students could immediately feel the effects of greater stiffness and greater damping...” [45], or the use of an Omni haptic device where “the user interacts with the VR application through a haptic device, imposing and feeling the reaction forces on the beam, which are related to the mechanical characteristics of the material” [46], or even those described in “nanomanipulator applications for tactile feedback and to manipulate objects such as viruses that are nanometer-sized” [47].

In fact, the first author was first involved in the use of haptic interaction with a remote experiment between Brazil and Portugal reported in [48]. In this case, a live video of the behavior of a Portuguese experiment was available in Brazil, where the user was also receiving the corresponding force feedback by actuating the remote experiment. Using a lighter communication protocol with a network communication velocity of around 60Kbps, the mean rate of haptic communication data loss was 10% and the measured delay in response was 3.9 s. Simultaneously, video delay also had to be considered. Although the study proved to be exciting for all students and teachers involved, the mentioned constraints were not so positive for the “proximity sensation” which the authors intended to induce in users. Therefore, a hybrid solution (an application integrating the remote experiment and its virtual replica all together) was developed for use within Ethernet. In this solution, and to minimize additional delays, the feedback information available in the user interface would also feed the virtual reality. Even so, the delay between live video and the simulated device was still one constraint. Finally, a totally virtual system was used with haptic interaction.

By offering the students the combined use of both systems (remote and virtual experiments) and traditional lab sessions, some interesting conclusions arose. Students’ free comments reported that the use of haptic interaction makes the experiment interesting, allows a new interactivity with a system, “feeling” the material (reaction) and so increases perception and consequently studying efficiency. In fact, “feeling the beam reaction force in the user hand, he/she gets immersed in the experiment and this additional sense will help the user knowledge of Young modulus of materials together with the association of force magnitude/strain magnitude both displayed in the interface” [46]. These aspects arising from the virtual experiment strongly enrich the real one if they are used in a complementary approach. Returning to the “thirteen objectives”, it is clear that objective 13 is now totally observed by the virtual experiment as opposed to the other previously discussed experiments in section A. Many of the other objectives are still observed. Deeper evaluation of these potentialities will require a very well structured survey, now in preparation, in order to convey reliable results. In any case, it is possible to state that the use of all these tools in complementary ways will provide the students with better opportunities and complementary knowledge. This means that, once again, online experimentation may contribute towards attaining higher-order experimental skills.

5. **Conclusion**

Carefully conceived online laboratories provide a valuable contribution to the acquisition of higher-order experimental skills in Science, Technology and Engineering. Although the offer of online laboratories is increasing, there is still a long way to go, namely in pedagogical and didactical terms, i.e. on how to best combine the potential of virtual and remote labs in order to help students become fluent in the language of Nature; in particular, allowing them to learn how to predict the sort of results virtual and remote labs return, in a situation similar to the Turing test, i.e. without knowing in advance which lab type (virtual or remote) they are accessing.

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