Remote Experiments as Virtual Labs? Examples with Pendulum

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Abstract

The contribution presents the technology and examples of real remote and virtual experiments that contain pendulum. This experiment topic has played an important role in the history of time measurement and understanding gravity, therefore it is still included in school curricula and lab assignments. We present a new real remotely controlled physics experiment that is available at any time, from anywhere, and for everyone and that can be linked with virtual experiments (simulations). The real remote experiment technology is based on our universal "iSES Remote Lab SDK" platform as well as other 18 remote labs available online. This SDK, which is used for easy creation of new remote experiments even by non-programmers, is also described.

In the introduction, we recall first PC-aided experiments with pendulum, their features, technology, and outcomes. Then we describe our new real remote experiment. It offers opportunity for an experimental study of several dependencies between experimental parameters like period vs. deflection or period vs. length, with a goal to determine the experimental value of local gravity acceleration g. Our real remote labs may be accessed with common web browsers, they feature live video of the experimental setup and a possibility to record and download own experimental data for further processing with dedicated software. Furthermore, first outcomes of the WorldPendulum (WP@ELAB) Project are discussed. The project aims to create and publish 20 identical online pendulum remote experiments worldwide in order to study the dependence of the gravity value g on latitude.

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Keywords

Remote Laboratory. Virtual Laboratory. Pendulum. ISES Remote Lab SDK. Gravity of Earth. Projekt WP@ELAB

INTRODUCTION

History of pendulums

Galileo Galilei is considered to be the first scientist who studied pendulums experimentally (around 1582 by the swinging motion of a chandelier in the Pisa Cathedral). He also found that the period is independent of the mass of the pendulum and proportional to the square root of the length of the pendulum. He measured time using his heartbeats because no precise clocks were available. Later he proposed to use pendulum clocks for precise time measurement. The idea was realised after Galileo's death. Historicians believe that pendulums had been used in the 1st century in China as a simple seismographs. Also Leonardo da Vinci is the author of many drawings of pendulums as timekeeping applications.

The first pendulum clock was constructed in 1656 by the Dutch scientist Christiaan Huygens. Best accuracy achieved was around 15 seconds of drift per day. In 1671 French astronomer Jean Richer found during his expedition from Paris to Cayenne in French-Guyana that pendulum clock was 2,5 minutes per day slower at Cayenne than at Paris. He concluded that the force of gravity was lower at Cayenne. The study of this dependency in school setting is also the goal of the WP@ELAB Project. Due to the dependence of period on temperature, air pressure and the influence of air friction on the pendulum movement as well, pendulum clocks have been replaced with cheap and available quartz crystal oscillator clocks since 1927.

First remotely controlled pendulum

Real remote labs became part of experimental physics education many years ago. First remote labs were described in (Aktan, B., Bohus, C., Crowl, L., Shor, M. H., 1996). Probably the most significant contribution concerning remote pendulum was the German project World Pendulum (Gröber, S., Vetter, M., Eckert, B., Jodl, H.-J., 2007). Here several identical pendulum experiments were offered online, enabling the study of the dependence of gravity on latitude and height above sea level. These pendulums were situated in:

1. Germany (Kaisersesch, latitude: N50.23°, 455 m above see level)
2. Germany (Hermannsburg, N52.83°, 55 m)
3. Italy (Napoli, N40.83°, 6 m)
4. Yemen (Aden, N12.80°, 25 m)
5. Latvia (Riga, N66,93°, 11 m).

German pendulums consisted of a steel sphere, a wire and a precision suspension. Their length 2,7 m corresponded to a pendulum period of one second. The initialization of oscillation was realized with movable electromagnet on a sledge moving on tracks. After the electromagnet is switched off, the sphere is released to oscillate. An important part of the experimental setup is a photogate to measure period of the pendulum to determine the

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Earth´s gravitational acceleration *g*. Accuracy of time measurements around 0.1 ms was determined using the sampling frequency of counters connected to the optical gate. The deflection of pendulum could not be measured in order to decide whether oscillations are harmonic. It was only possible to set the initial angle of deflection, afterwards the time period of the pendulum could be measured. The experimental value of local gravity acceleration *g* was determined with corrections considering temperature dependence of the length so the temperature had to be measured, too. Two items of assignment were:

1. Measurement of the Earth´s gravity acceleration at one of the five locations in the model of the physical pendulum.
2. Measurement of the dependence of the swing period of the pendulum on the initial angle of deflection.

Unfortunately, the control web page (see Figure 1) is not available anymore because it was based on Java applets, which required JAVA SE 6.0 Runtime environment (JRE) available from the Oracle Java archive (nowadays with security vulnerabilities and many warnings that make remote measurement impossible).

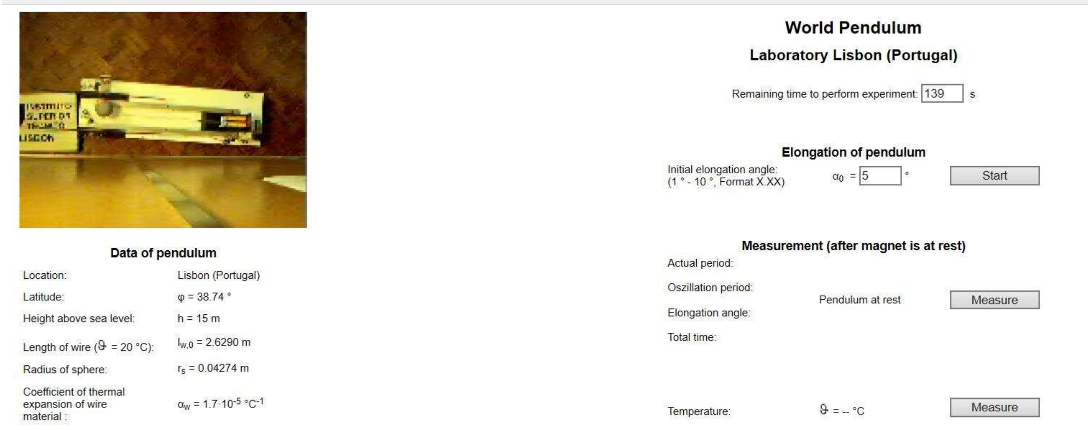

Figure 1: Control web interface of World Pendulum in Lisabon laboratory, 2007
(http://rcl-munich.informatik.unibw-muenchen.de/worldpendulum/eng/lab_lissabon.htm)

The German (later also Portuguese) World Pendulum remotely controlled experiments (RCLs) were created in 2007 and unfortunately were not upgraded to be accessible by smartphones in the following years. Their live video quality was poor. However, we must appreciate their first successful experimental study of the dependence of gravity on latitude using remote measurement over the Internet.

Pendulum in Trnava (Slovak Republic)

The other significant contribution was the Slovak remote pendulum (Schauer, F., Majerčík, P., 2009). It was created in 2009 and situated in the University of Trnava. It was based on the ISES platform (E-laboratory Project, 2002) and contactless reading of angle deflection using two dynamometers (see Figure 2 A). The swing period of pendulum could be measured with an optical gate. The actual measurement of the deflection angle from dynamometer readings was challenging. (Schauer, F., Majerčík, P., 2009).

The control web interface (see Figure 2 B) was based on the software development kit “iSES Remote Lab SDK”, see (Lustig, F., Dvorak, J., Kuriscak, P., Brom, P., 2016) that is

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described further below. It involves control objects (buttons, sliders), display objects (graphs, values), experimental data recorder and downloader and live video stream of the oscillator and its initialization mechanism.

The items of assignment were:

1. Determination of the local gravitational acceleration.
2. Study of the dependence of swing period on initial angle of deflection.
3. Determination of kinetic, potential, and total mechanical energy.
4. Study of damping caused by air friction.

Unfortunately, this remote lab is not online any more as of time of the publication.

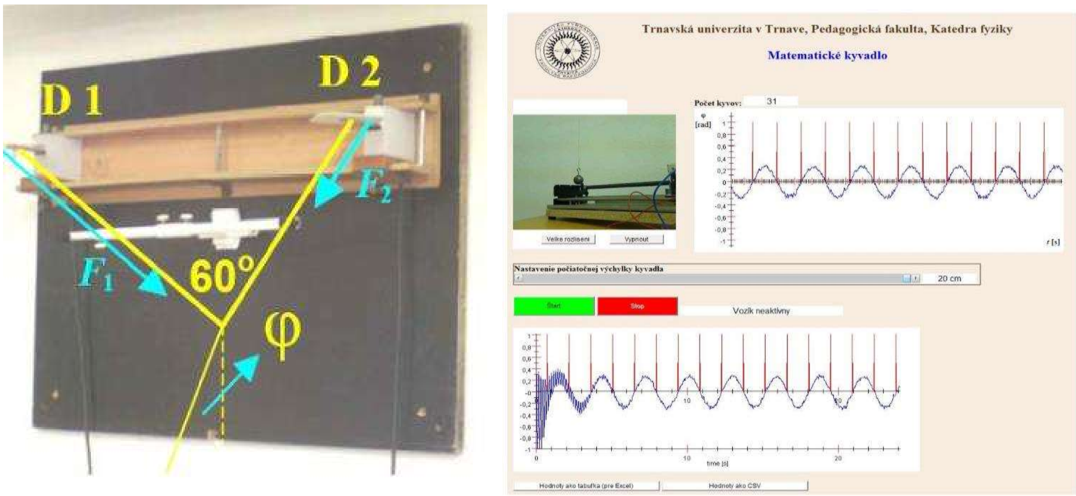

Figure 2: A: Pendulum - detailed view on experimental setup with two dynamometers (D1, D2) for determination of angle deflection of the pendulum.
B: Control web interface of the remote laboratory experiment Pendulum in the University of Trnava (Slovak Republic), offline at the time of the publication.

Pendulum in the new project World Pendulum WP@ELAB

A successor to German and Lisabon (Gröber, S., Vetter, M., Eckert, B., Jodl, H.-J., 2007) pendulum project has formed in 2019 – World Pendulum Alliance (Santos, Fernandes et al., 2019). It is a federated initiative of several universities devoted to create a network of pendulums at various latitudes with the objective of mapping local gravity differences at different locations. The constellation will consist of 20 primary experiments (with basically the same hardware parameters as the original German one) and 120 secondary experiments to be deployed in partner universities in the following years. Most of the installations should be eventually located in South America.

All experiments are supposed to be accessible remotely by high-school or university students, allowing them to perform various educational activities. Since so many installations were planned to be deployed, a careful IT infrastructure design had to be implemented. The data flow from individual experiments (through RESTful API) would be restricted to a private VPN and centralised in servers located in Lisabon. Those servers will expose the controls and measured data to the outside world through websockets according to the Smart-Device Specification. This will allow the WPA experiments to be accessible

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using the already available GoLabz (www.golabz.eu) and Graasp (www.graasp.eu) framework as well as through its own portal.

In addition to remote experiments, a few MOOCs will be deployed. Educational content will go beyond the basic pendulum experiment and will include energetic balances and oscillation damping, tidal studies and variations of pendulum period with latitude, altitude, pendulum length etc.

The real overarching goal of this project is to promote cooperation between physics education institutions in Europe and South America. Teams from Europe are in process of visiting South American universities and disseminating the technical and educational knowledge required to install, maintain and use the pendulum constellation. South American universities are being supported in creating a science dissemination centers and cooperating with local smaller educational institutions, spreading the project reach even further. The project is still in the development phase as of writing of this contribution.

Pure simulated virtual pendulum laboratories

There are also a virtual on-line pendulum experiments, which should be noted here. Well-known collection of physical applets (PhET) containing over 150 virtual experiments offers a pendulum at:

http://phet.colorado.edu/sims/html/pendulum-lab/latest/pendulum-lab_en.html

Another applet collection (Walter-Fendt) also provides a pendulum simulation at:

https://www.walter-fendt.de/html5/phen/pendulum_en.htm

Our team has previously proposed a connection of e-text, virtual and remote experiments under the “integrated e-learning” strategy (Schauer, F., Ožvoldová, M., Lustig, F., 2009).

METHODS – OUR PENDULUM EXPERIMENT

Pendulum in Prague (Czech Republic)

One of the more elaborate remote experiments with pendulum is located in our laboratory at Faculty of Mathematics and Physics of Charles University in Prague. The experiment has been just recently launched (2019), is fully functional and non-stop accessible using standard browser at: http://kdt-40.karlov.mff.cuni.cz.

Experimental design

This remote experiment presents a pendulum with variable length (possibly the only one currently online worldwide). It is equipped with two stepper motors, one controlling the length, the other one setting the initial deflection (See Figure 3). Pendulum period is measured using a photogate, deflection is measured using water-based potentiometer (this provides significantly decreased friction). Under the ball, there is a small water reservoir with two electrodes. These electrodes are connected to a constant voltage. A miniature needle is attached to the pendulum ball, touching the water surface. Because the whole pathway up the pendulum pivot is conductive, one can measure the instantaneous deflection by measuring the voltage between the pivot point and one of the electrodes.

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The experimental setup is monitored by two cameras that provide additional feedback to the users inside the controlling web interface. The interface itself displays real-time graphs of deflection and photogate signal. Users can trigger a data recording session and later download measured values as a CSV file or display them within an html table. They can later process the measured data in their own software.

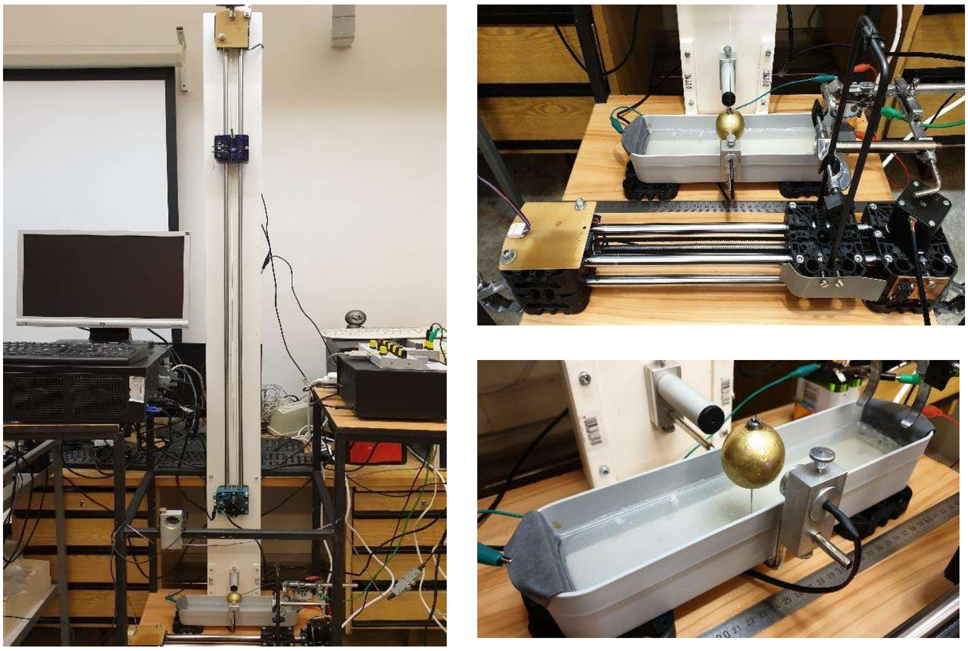

Figure 3: Arrangement of pendulum in Prague (Czech Republic, 2019). Image on the left shows an overview of the whole experimental setup. In its center, an adjustable pendulum length (1.6 m to 0.8 m) mechanism can be seen. In the top right image, there is a pendulum ball with photogate and a motorised initial deflection mechanism (9.5 or 6.5 cm). Bottom right image displays a detail view of the water-based potentiometer.

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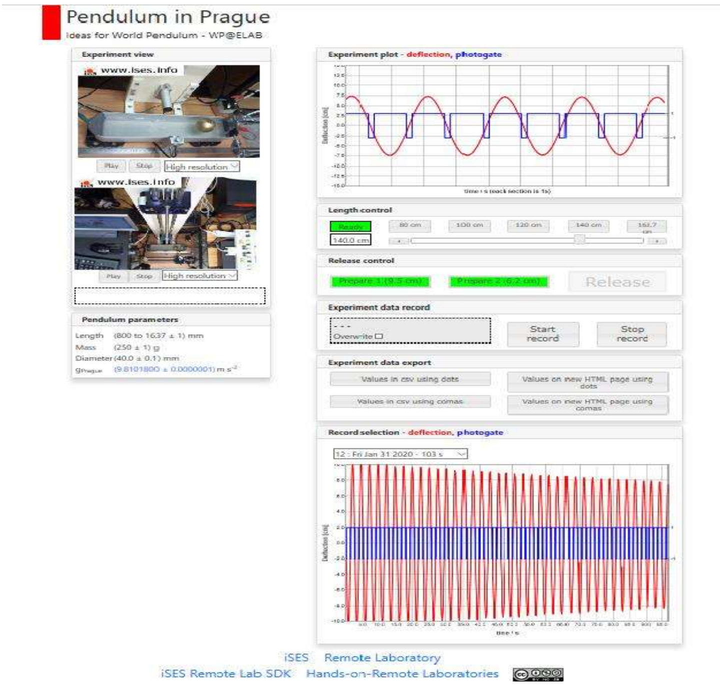

Figure 4: Control web interface of the remote laboratory experiment Pendulum at the Charles University of Prague (Czech Republic, 2019). (http://kdt-40.karlov.mff.cuni.cz).

Software architecture

We have built a software kit of "iSES Remote Lab SDK", described in detail in (Lustig, F., Dvorak, J., Kuriscak, P., Brom, P., 2016). This software kit is originally developed for ISES measurement hardware (Schauer, F., Kuřitka, I., Lustig, F. , 2006) but also has a support for Arduino boards.

Server-side part of a remote experiment consists of experimental hardware connected to a dedicated computer, which runs *MeasureServer* and *ImageServer* applications. *MeasureServer* provides two-way communication with the hardware, while *ImageServer* creates a video stream captured by a webcam. As the real-time data connection is realized using the WebSocket technology, a *web server* (e.g. free *NGINX*) must also be installed and running. In most of our experimental setups the web server runs on the same dedicated computer and serves both user interface in a form of webpage and relays the WebSocket connection to the MeasureServer. Clients connect to the experiment through regular web browsers. Client browser has to support JavaScript and WebSocket technologies. These are however standard features of all modern browsers in most devices and are required by various other internet applications. In case the WebSocket protocol is not supported on client side, connection automatically switches to HTTP fallback so that measurement is still possible, although with degraded performance.

In Figure 4, you can see the web interface of the remote Pendulum in Prague. It is built in JavaScript, therefore it's possible to use it even with mobile devices.

We have prepared a library of approx. 20 JavaScript components (widgets). Widgets are highly configurable and provide many thoroughly documented options, which are available by default and which allow even non-programmers to build a complex measuring and controlling interface with data and video transfer. Among built-in features, users have

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access to real-time spline interpolation, simple processing, export of data in various formats, graphical output and other sophisticated functionality. User interface widgets are mostly based on JQuery and few other freely available JavaScript libraries that are distributed together with the SDK. By using these standard elements, the user interface visual design is also highly customizable. Web-page developers are able to alter the default design using standard methods (mostly CSS) to fit the webpage in which the interface is embedded. Widgets cover all standard interface elements that are needed for design and control of the experiment.

For non-experienced experiment designers we have prepared a Collection of pre-built simple experiments such as remote analogue record of one quantity (e.g. temperature), remote analogue control of one channel (e.g. switch relay), remote control of digital inputs and outputs, time dependence of two or more quantities, XY dependence of input and output quantities, data record, data export, WEB camera stream etc. The examples have the simplest possible code and mostly use default settings for all the components. These simple interfaces can be arbitrarily merged and combined so even beginners are able to rapidly develop complex interfaces. They can immediately control their own remote experiments via mobile phone or tablet. This set of examples can be accessed online on (E-laboratory Project, 2002). Many experiments also contain an assignment, e-texts with the theory, and examples of data processing.

Educational goals of our remote experiment Pendulum

The possibility to set and change the pendulum length, its initial angle of deflection and to easily record and download experimental data offers interesting labwork with advanced statistical and graphical data processing for students. Properties and physics of pendulum may be studied using variety of dedicated software (MS Excel or similar spreadsheet processors, gnuplot, etc). Users may perform their remote measurements of these dependencies:

1. Swing period *T* of the pendulum versus its length *l*.
2. Swing period *T* of the pendulum versus (initial) angle of deflection α.

The swing period *T* can be determined simply from the optical gate signal or sophisticatedly using a harmonic function fit of voltage readings from the water-based potentiometer. Within advanced graphical processing using the model function

$$T = T(l) = 2\pi\sqrt{\frac{l+c}{g}}$$

students may verify that period *T* is proportional to the square root of the pendulum length *l*. Moreover, they can determine two parameters with physical meaning: the local gravity acceleration *g* and (probably positive small) length correction *c* considering the true rotational axis position of the pendulum oscillations and the systematic error of the length reading (in fact, only the changes, differences of *l* are set and known absolutely). Sample graphical processing of the first dependence can be found in the Figure 5 (see section Results). The local gravitational acceleration is then one of the fitted parameters.

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Another educational approach to pendulum experiment is presented in (Beňačka, J., 2009) which gives a power series solution to the pendulum equation that enables to investigate the system in a purely analytical way.

RESULTS

Measurement was performed for 5 various pendulum lengths. The period was determined from the optical gate signal as the average value of 3 measurements with estimated error – see the results in the Table 1 and graph in the Figure 5.

Table 1: Sample results of the measurement and processing.

Pendulum length [cm]	Period (with error) [s]	Final fit parameters with asymptotic standard error determined by Gnuplot
163.7 140.0 120.0 100.0 80.0	2.566(3) 2.374(3) 2.200(3) 2.007(2) 1.794(2)	Model function: $T(l) = 2\pi\sqrt{\frac{l+c}{g}}$ Local gravity acceleration: *g* = (980.4 ± 2.3) cm·s^{-2} Length correction: *c* = (0.01 ± 0.28) cm

In separate set of measurements we have confirmed that the presence of friction does not introduce a measurement error greater than the one introduced by the photo-gate sampling rate.

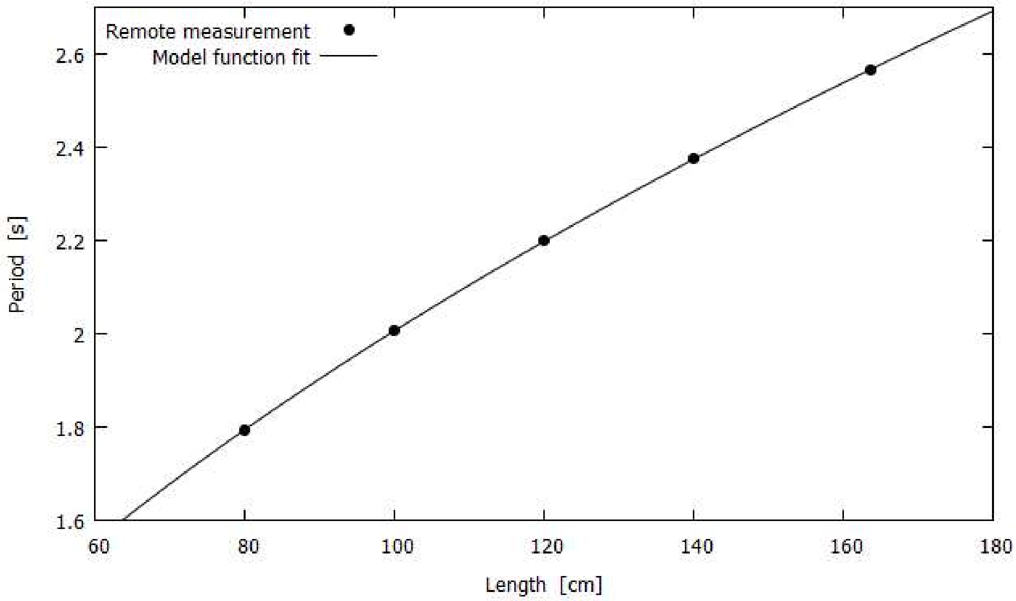

Figure 5: Model function fit of 5 average values (n = 3) of the pendulum period with goal to determine local gravity acceleration g using scientific freeware Gnuplot.

DISCUSSION

In our view, the main appeal of virtual laboratories is their easy on-line accessibility, rather than their pure simulated nature. In this perspective, remote experiments offer

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almost the same on-line convenience, while preserving real-life intricacies of experimental measurements such as noise or the need of proper operation of the equipment.

In our other works we have also attempted to extend remote experiments in the opposite direction by proposing a "hands-on-remote" philosophy (Lustig, F., Brom, P., Kuriščák, P., Dvořák, J., 2018), which integrates hands-on experiments in the classroom with a later possibility of accessing the hardware remotely.

CONCLUSION

In this contribution we have reviewed a remote and virtual experiment technologies involving a pendulum. We have presented our unique experimental setup with variable pendulum length, its detailed software architecture (based on iSES Remote Lab SDK) and sample measurement results.

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