

Article

Design and Development of an Ultra-Concurrent Remote Laboratory for Projectile Motion Experiments

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Abstract

Experimentation in science education faces significant access limitations, both in face-to-face and distance learning settings; in light of this situation, remote laboratories are emerging as a strategic solution. The aim of this study is to present the design and development of an ultra-concurrent remote laboratory focused on the study of projectile motion. Using the Design-Based Research methodology, the resource has been structured around an iterative five-phase approach: design, data capture, development, test and improvement, and integration. The data acquisition system was developed using a hardware setup comprising a projectile launcher, photo gates, a digital interface and a time sensor, implemented and managed via the LabsLand platform. The laboratory integrates semi-parabolic and full-parabolic configurations via an interactive interface that guides the user from connecting components to the multimedia observation of real experimental data. The results of the experimental validation confirm the system's viability, as the data obtained compare with ideal kinematic equations and reflect, as expected, the behaviour and physical limitations of the real-world environment. This laboratory offers a potential pedagogical advantage, reporting percentage errors around 3–11%, as it exposes students to experimental uncertainty whilst simultaneously ensuring simultaneous and free access for multiple users in science education.

Keywords: remote laboratory; projectile motion; ultra-concurrent

1. Introduction

Experimental activities in science education are a cornerstone of learning, as they foster a range of essential skills in students. This contributes to the development of critical competencies for professionals in the fields of science and technology, such as precision in measurement, control of variables, modelling of phenomena, consolidation of concepts and interpretation of representational systems [1,2]. In various educational settings, access to experimental facilities and equipment is often restricted by limitations in infrastructure, resources and time [3]. This situation is particularly acute in distance learning; however, the implementation of technology-mediated laboratories is emerging as a strategic solution.

Remote laboratories (RLs) are educational resources that combine hardware and software, enabling experimental activities to be carried out remotely via the internet [4]. These resources have broadened access to experimental activities in various educational



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settings, facilitating the implementation of experimentation in science teaching [5]. In recent years, the Remote Experimentation Laboratory at the National Distance Education University (UNED), in collaboration with LabsLand, has promoted the development of RLs for the teaching of physics, chemistry and biology [6].

These laboratories enable the collection and analysis of real-world data, taking into account the experimental uncertainty associated with the measurements [7]. The fact that these laboratories are always available makes them easily accessible to students who are constrained by time or geographical location [8].

These laboratories can be divided into two types (Figure 1): Real-time Laboratories, in which users operate the experimental equipment in real time whilst observing the experiment via a live interface, and Ultra-concurrent Laboratories (UL), which are based on records of real experimental data that have been previously collected and processed. Unlike Real-time Laboratories, ULs allow multiple users to access the same experimental experience simultaneously, making them suitable educational resources for large student populations. The proposed laboratory is managed via LabsLand, ensuring high scalability [9].

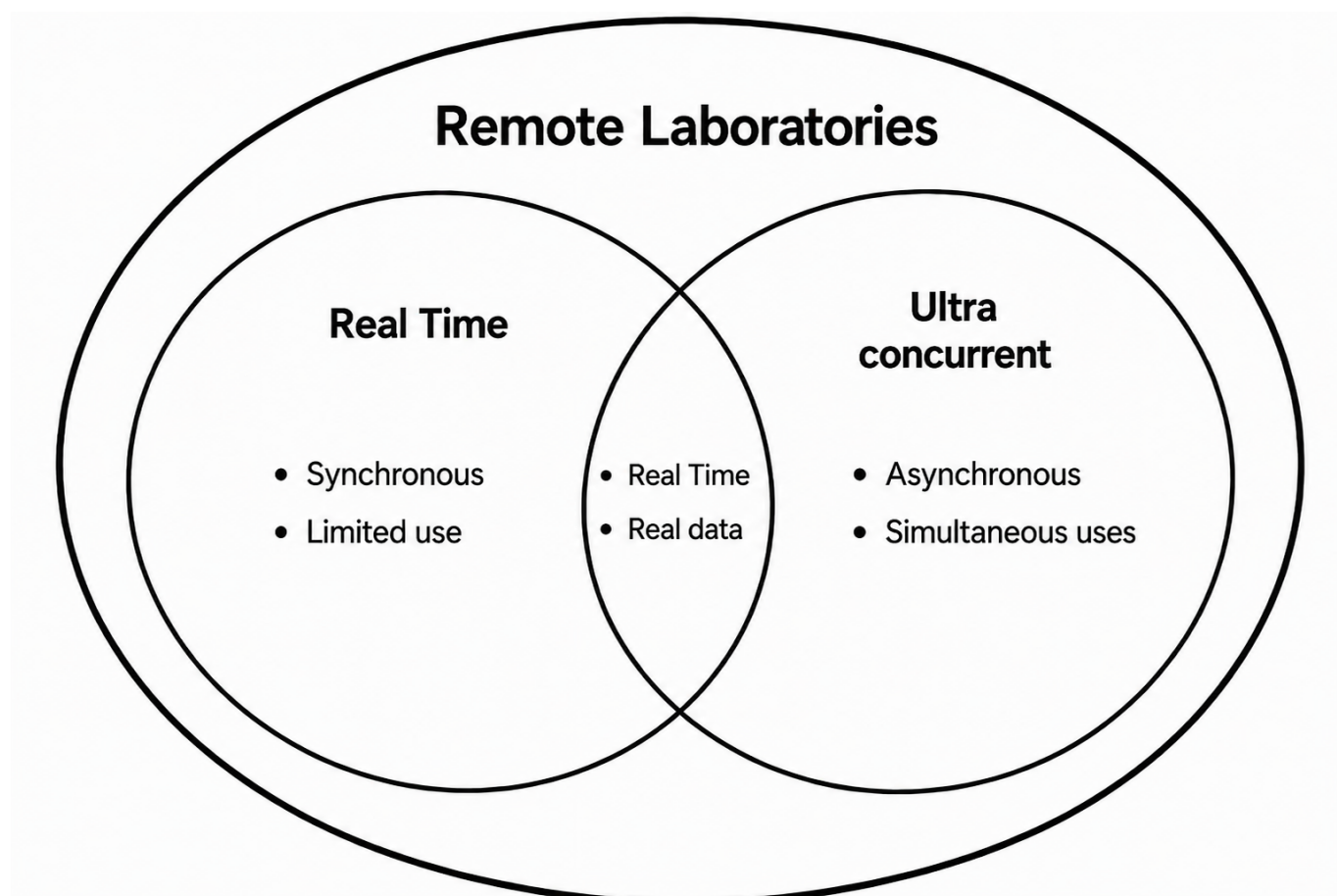


Figure 1. Characteristics of different types of remote laboratories [10].

Scalability constitutes one of the main differences between the various types of RL. In real-time laboratories, the service capacity depends directly on the available equipment, so expanding access requires incorporating new systems or managing reservations [11]. Some laboratories, such as VISIR, achieve high levels of concurrency, although they remain dependent on the installed physical infrastructure [12]. Unlike these systems, ULs reconstruct the experiment from previously recorded real data, so the number of users who can access the laboratory simultaneously depends mainly on the web infrastructure rather than

on the experimental equipment. This makes it possible to serve large student populations with a single experimental setup.

Projectile Motion

The motion of projectiles is one of the fundamental topics in physics education and is usually studied through hands-on experiments, simulations and virtual experiments [13]. Although these resources allow the trajectories of projectiles to be visualised, they do not always replicate the conditions of a real-world experiment.

The study of projectile motion often presents various conceptual difficulties for both students and teachers. Among these is the belief that objects continue to move due to a force or impetus they carry with them from the moment of launch. Consequently, they often assume that a launched object initially moves in a straight line and begins to fall only when that impetus is exhausted, that an object dropped from a moving vehicle falls vertically, or that there must be a force in the direction of motion [14]. Furthermore, one of the main difficulties lies in understanding that the projectile's motion results from the combination of two independent motions. Students often analyse the components of velocity mechanically, confuse horizontal throws with free fall, and interchange the horizontal and vertical components [15]. Evaluating the effectiveness of this laboratory in addressing these conceptual difficulties will be the subject of future research with students and teachers.

Despite the gradual growth in the use of RLs in physics education, their application to the study of projectile motion remains limited [16–18]. This situation presents an opportunity to develop an experimental resource designed to study this topic. RLs offer an alternative for conducting experimental activities that can be used in both face-to-face and distance learning settings.

A literature review was conducted on studies that specifically address the use of RLs for the study of projectile motion. A total of four articles were identified. Three of them were developed by a research group at the Polytechnic of Porto based on the same experimental proposal. The first presented the design of an RL for conducting projectile launch experiments, the objective of which was to allow students to determine the acceleration due to gravity and analyse the dependence of motion on various parameters [19]. The second applied Design State Exploration techniques to this proposal [20], while the third compared two methodological approaches (professional and academic) used during its construction [21].

A fourth article proposed a model based on the remote visualisation of video recordings of a physical apparatus used with engineering students, without incorporating remote control of the equipment via the Internet [22]. Unlike these works, the laboratory presented in this article incorporates an ultra-concurrent architecture and brings together, within a single experimental environment, semi-parabolic and full-parabolic configurations, along with interactive elements designed to encourage active user participation.

The aim of this article is to present the design and development of a UL dedicated to the study of projectile launch.

2. Methodology

The design and development of the RL was based on an iterative approach, within the framework of Design-Based Research. This approach was structured in five phases (Figure 2): design, data capture, development, test and improvement, and integration. At each stage, adjustments were made to improve the laboratory's performance, enabling the optimisation of both its technical components and the conditions for accessing, viewing and retrieving experimental data.

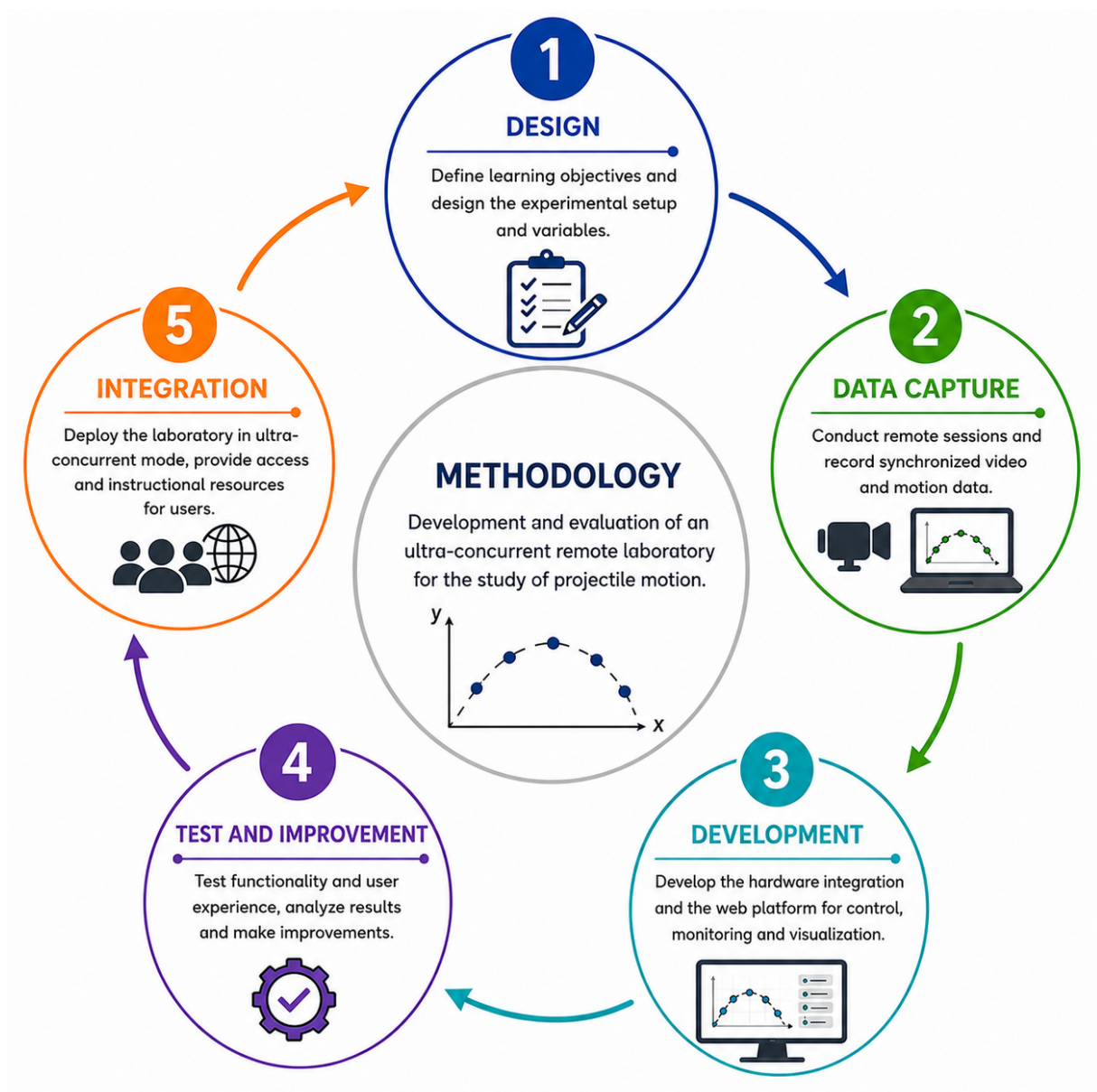


Figure 2. Development phases of the Projectile RL following an adaptation of the Design-Based Research methodology [23].

2.1. Design

The design was based on the objective of developing a laboratory capable of analysing the main physical conditions associated with parabolic motion. To this end, it had to enable the study of semi-parabolic and full-parabolic trajectories, as well as variations in the launch angle and maximum range. The equipment used was a data acquisition system comprising (Figure 3):

- A projectile launcher;
- Two photo-electric sensors attached to the projectile launcher, for recording the projectile's initial velocity;
- A time sensor, for recording the projectile's flight time;
- An interface, for converting signals into digital data, which was then transmitted to a computer;
- Software for data visualisation and collection.

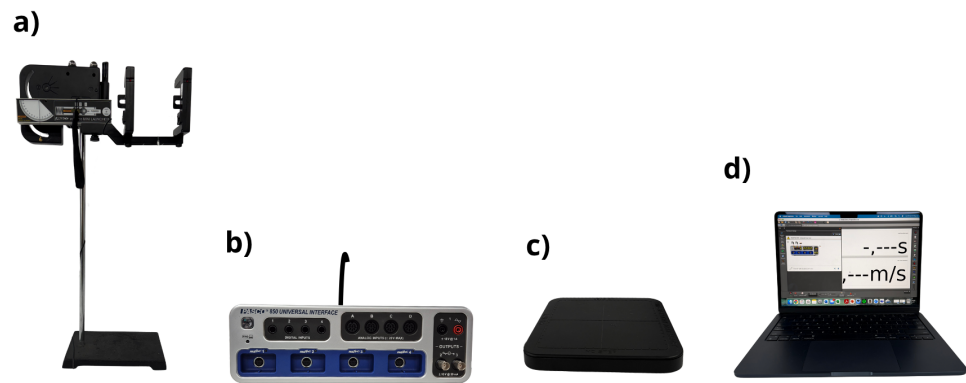


Figure 3. Equipment used in the projectile laboratory: (a) launcher, (b) interface, (c) timing sensor, and (d) computer running the data visualisation and collection software.

The laboratory's design comprises two experimental setups. The first involves launching a projectile at three different launch intensities from a specific height and at an angle of 0° , producing a semi-parabolic trajectory. The second configuration involves launching a projectile using three different angles (35° , 45° and 55°) and two launch intensities, generating full-parabolic trajectories. A third launch intensity was initially considered; however, this was ruled out due to the projectile's poor visibility in the audiovisual recordings, which limited its use within the laboratory.

For the audiovisual recording, multiple recordings were made to capture the projectile's trajectory in both configurations. This allowed for an assessment of the visibility of the elements and the clarity of the trajectories. The numerical data obtained were analysed in terms of their consistency with the audiovisual recordings and their physical consistency with the expected behaviour of projectile motion.

2.2. Data Capture

For both setups, audiovisual recordings and experimental data were collected during the projectile launches. In the first setup, the projectile was launched horizontally from a height of (53.4 ± 0.1) cm towards the timing sensor. In the second setup, the timing sensor was positioned at the same height as the launch point, enabling the complete trajectory of the projectile to be recorded.

During the launches, a front view was used to observe the projectile's trajectory, alongside a top-down view from the timing sensor, enabling the exact point at which the projectile ended its flight to be identified. Furthermore, the projectile's initial velocity was recorded using photo-gates attached to the projectile launcher, and the flight time was measured using the timing sensor. The horizontal range was determined using a graduated scale located next to the time sensor.

The collected data was incorporated into the software developed by LabsLand, which processes and converts the information into the dataset used internally by the RL.

2.3. Development

A simulation was developed using the audiovisual recordings and experimental data obtained from the launch configurations. The recorded footage underwent a process of refinement and editing, taking into account the visual clarity of the projectile's trajectory and the consistency between the experimental measurements and the information obtained from the sensors.

Subsequently, in collaboration with LabsLand, an interactive interface was developed that integrates the audiovisual recordings with the experimental data obtained in each trial. Furthermore, it allows students to interact with the setup during an initial phase of

connecting components, followed by the observation of two perspectives of the projectile launch and access to the data resulting from each launch. These sets of experimental results are assigned automatically and randomly due to the highly concurrent nature of the laboratory's architecture.

2.4. Test and Improvement

Multiple tests were carried out to assess the laboratory's performance, both in terms of visualising trajectories and recording experimental data. During this stage, adjustments were made regarding the synchronisation between the audiovisual recordings and the data obtained by the sensors, as well as the organisation of the information presented within the interface.

One of the main aspects considered was the clarity with which the user could observe the projectile's movement during the different experimental configurations. This made it possible to identify configurations that were not suitable for implementation within the laboratory, as was the case with one of the launch intensities for the full-parabolic trajectory, which was ruled out due to the poor visibility of the projectile.

Adjustments were also made to improve interaction with the laboratory during the equipment assembly phase. These modifications sought to emulate the equipment connection process more realistically, with the aim of creating an experience closer to that of the in-person experimental practice.

2.5. Integration

The integration of the laboratory into the LabsLand platform made it available to users. The platform includes an overview of the laboratory, interactive elements and the sections required for carrying out the practical experiments.

During this process, the proper functioning of the audiovisual recordings, experimental data and interactive elements within the laboratory interface was verified.

The availability of the laboratory on LabsLand simplifies the management of the facility, allowing multiple users to access it simultaneously. Furthermore, it ensures the laboratory's continuous operation through a platform specialising in the management of RLs.

3. Results

This section presents the UL developed for the study of projectile launch, as well as the experimental results obtained from it. First, the sections comprising the interface and the elements incorporated for the conducting of the experiments are described. Subsequently, the two launch configurations are presented, together with the experimental data associated with each of them.

3.1. Laboratory Developed

The laboratory is available on the LabsLand platform. Once accessed, the main interface is displayed, which is divided into four sections: introduction, configuration, connection, and observation. Each section is described below.

3.1.1. Introduction Section

This section provides users with an introductory video and a diagram of the equipment used during the experimental session (Figure 4). The video provides a general overview of the theoretical and practical aspects of projectile launch, as well as the basic principles for using the RL. Furthermore, the diagram helps users identify the various components of the experimental setup. In addition, a timer in the top-right-hand corner limits the duration of the user's session to one hour.

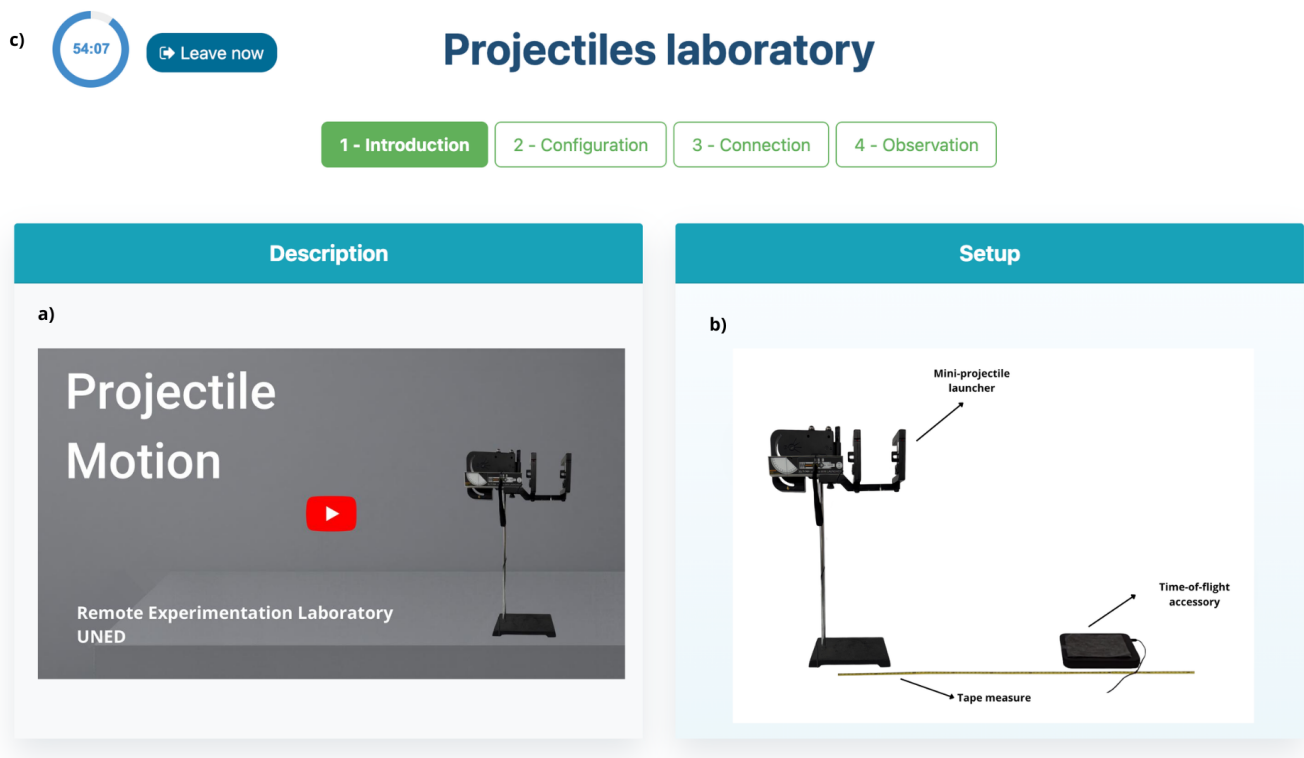


Figure 4. Introduction section on the remote projectile laboratory interface. (a) Video, (b) equipment diagram and (c) timer.

3.1.2. Configuration Section

This section allows the user to select the experimental configuration they wish to carry out. First, they must choose between a full-parabolic or a semi-parabolic trajectory. For the full-parabolic trajectory, the user selects the launch intensity level—low or medium—as well as the launch angle, which can be 35° , 45° or 55° . On the other hand, if the semi-parabola setting is selected, the user must choose the launch intensity level from low, medium or high; in this case, the launch angle remains fixed at 0° . Figures 5 and 6 show the configuration options for a semi-parabola and a full-parabola, respectively.

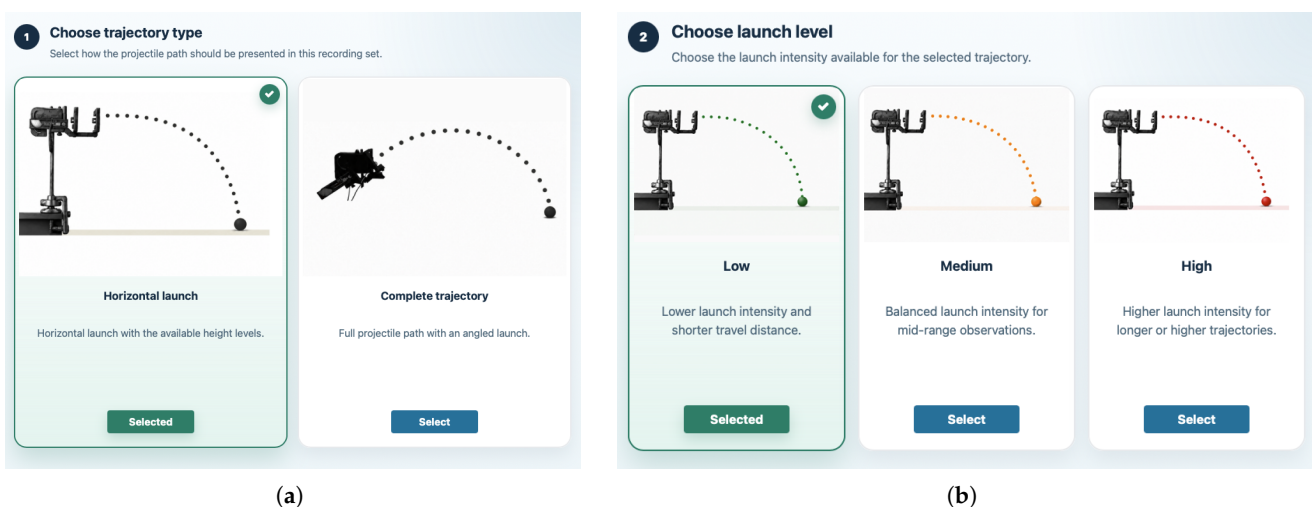


Figure 5. Configuration options for the semi-parabola at the remote projectile laboratory.

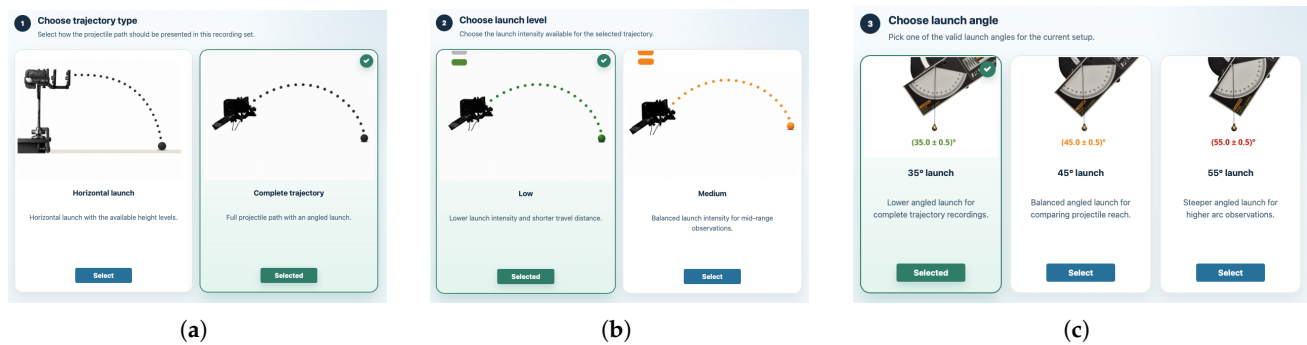


Figure 6. Configuration options for a full-parabolic trajectory at the remote projectile laboratory.

3.1.3. Connection Section

Once the desired settings for the experimental activity have been selected, the user is directed to the connection section. This section is designed to be as dynamic and realistic as possible, with the aim of providing an experience that closely resembles the real thing and allowing users to understand all the connections behind the equipment used during the experiment.

Using a step-by-step guide with indicators, all the necessary connections are made to use the measuring equipment, just as one would in a practical experiment (Figure 7). To this end, the screen displays a summary of the previously selected settings, a panel showing all the items required for the experiment, and connection points from which the various cables needed to make the relevant connections emerge, along with a yellow indicator showing where each cable should be connected. In addition, a counter is included on the right-hand side, listing the different connections to be made.

Measurement equipment connection

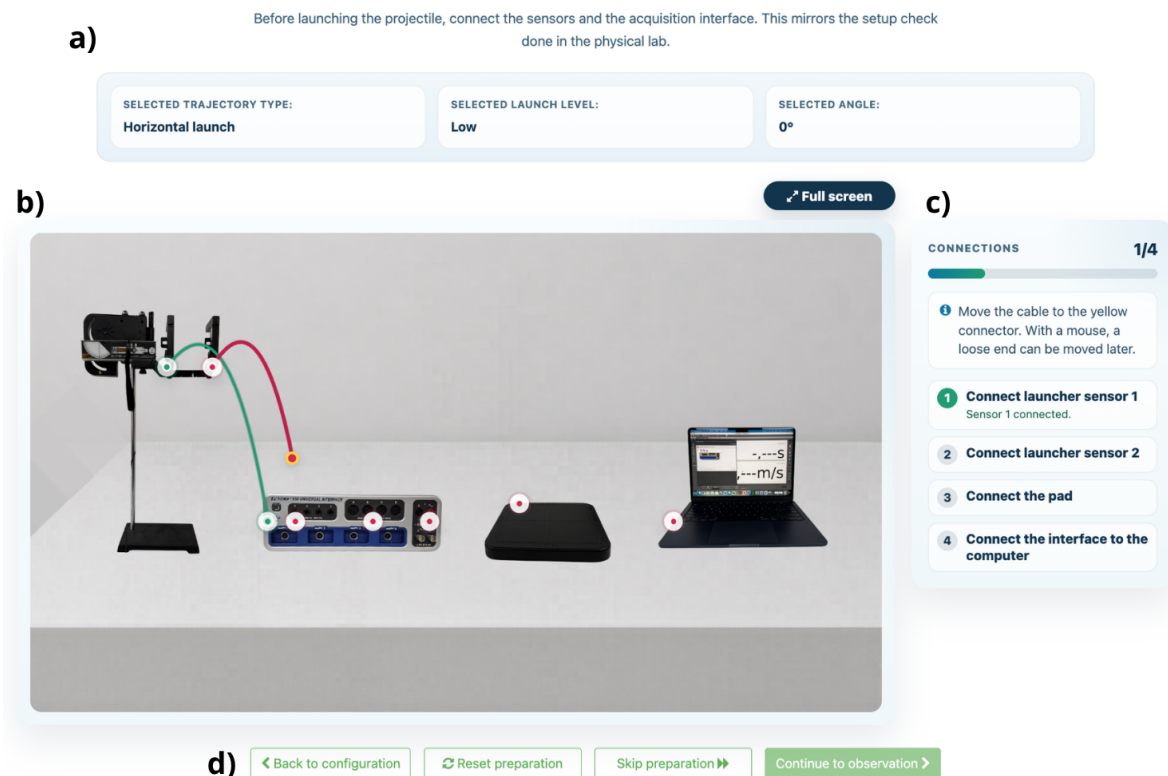


Figure 7. Remote projectile laboratory connection section. (a) Configuration overview, (b) equipment components panel, (c) meter and connection list, (d) control panel.

Finally, a panel appears at the bottom of the screen with a series of buttons that allow you to return to the settings to select other options, reset the cable connections if you make a mistake during the process, skip the setup and proceed to viewing. This last button is only unlocked once all connections have been made correctly.

3.1.4. Observation Section

This section shows the selected experimental setup (Figure 8). The interface displays a summary of the previously selected specifications on screen, along with two different views that simulate the experiment to be carried out. The front view shows the entire setup, allowing the trajectory of the projectile to be tracked until it strikes the timing sensor; meanwhile, the top view provides a close-up of the projectile striking the timing sensor and the measuring tape.

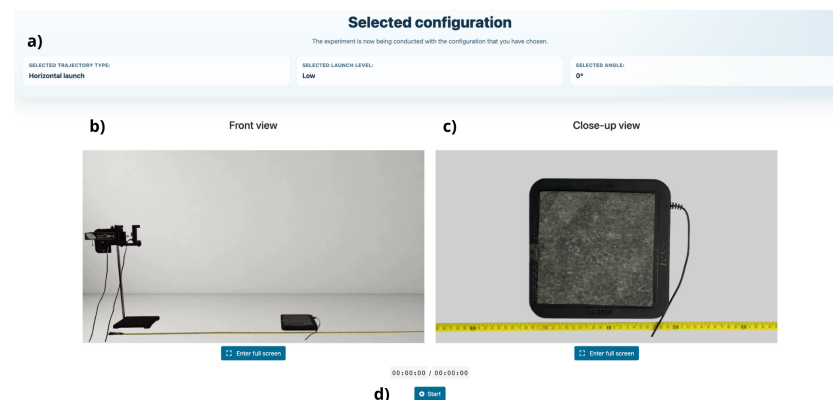


Figure 8. Observation section of the remote projectile laboratory. (a) Overview of the layout, (b) front view, (c) close-up view, (d) ‘Start’ button.

At the bottom is the ‘Start’ button, which allows you to run the simulation of the experiment. Once the launch is complete and the collision has taken place, an image of the result is displayed on the screen. At the top, the launch time and speed values are displayed along with their respective uncertainties. Furthermore, when you click on the point generated by the collision, a blue line begins to be drawn and guide lines appear, allowing for a more accurate measurement of the distance travelled (Figure 9).

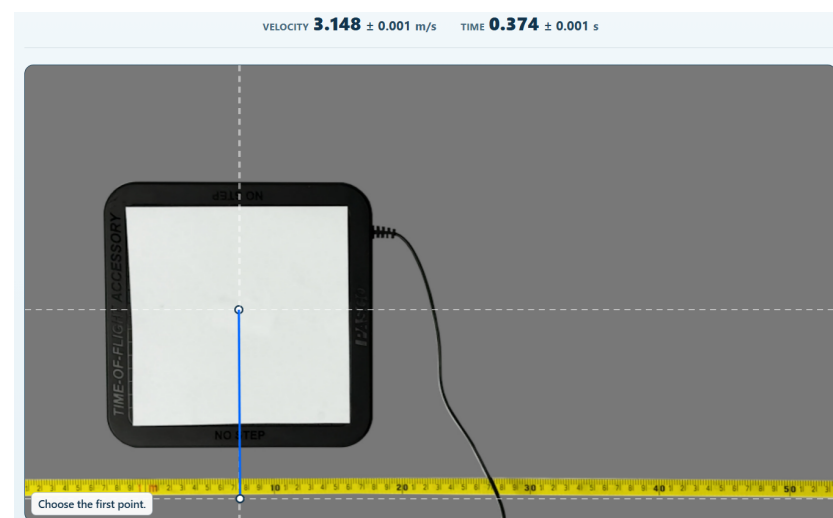


Figure 9. Results of the experiment, with measurement guidelines and the resulting values for speed and time at the top. The blue line represents the reference drawn by the student to measure the horizontal range.

This approach aims to ensure that students remain actively engaged during the experimental work, as the integration of measurement tools into the interface allows part of the experimental process associated with the manual analysis of results to be retained.

3.2. Experimental Results

In this laboratory, kinematic equations are used to model the motion of projectiles. To calculate the final position x_f of a projectile launched horizontally from a given height, taking its initial position as a reference x_i , the following equation is used:

$$x_f = x_i + v_x t \quad (1)$$

Knowing the initial speed v_i , the departure angle θ_i and gravitational acceleration g , the horizontal range R can be calculated using the following equation:

$$R = \frac{v_i^2 \sin 2\theta_i}{g} \quad (2)$$

The above equations enable the analysis of experimental data obtained in the laboratory. Below are examples of calculations based on experimental measurements of the initial velocity magnitude v_i , flight time and the projectile's final horizontal position. The calculations use a value for the acceleration due to gravity of $g = (9.77906 \pm 0.00341) \text{ m/s}^2$, where this is the best estimate of the acceleration of gravity determined on the whole continental territory of Costa Rica by the Monte Carlo method applied to the International Formula of Gravity [24]. Here the initial velocities, flight times, and horizontal ranges are reported as individual measurements rather than averaged values. This is because the data are collected in real time during the physical experiments and then provided to users of the RL as distinct datasets. The pedagogical objective is that each user can access multiple sets of raw data, confront the variability inherent in real measurements, and apply their own statistical treatment in terms of percentage error and uncertainty as part of the learning process. In future articles, the dynamics and impact of students performing their own statistical analyses of error and uncertainty will be explored in detail.

3.2.1. Semi-Parabola

The experiments in which the projectile followed a semi-parabolic trajectory were carried out by means of horizontal launches from a height of $(53.4 \pm 0.1) \text{ cm}$, using three different launch intensities.

Semi-parabola, Intensity level 1 (Low). For this configuration, the measured horizontal velocity and flight time were $v_x = 3.251 \text{ m/s}$ and $t = 0.313 \text{ s}$, respectively. Using these data and taking into account $x_i = 0$ in the Equation (1), the theoretical horizontal distance that the projectile must travel before striking the reference surface was determined:

$$x_{ftheo1} = 0 \text{ m} + (3.251 \text{ m/s})(0.313 \text{ s}) = 1.018 \text{ m} \quad (3)$$

The experimental result for the horizontal position of the projectile relative to the launch point, based on measurements obtained by the LR, is:

$$x_{fexp1} = (1.054 \pm 0.002) \text{ m} \quad (4)$$

The percentage error of the measurement relative to the calculated value is:

$$\%Error_{HP1} = \frac{|1.018 \text{ m} - 1.054 \text{ m}|}{1.018 \text{ m}} \cdot 100 = 3.536\% \quad (5)$$

Semi-parabola, Intensity level 2 (Medium), and Semi-parabola, Intensity level 3 (High), were similar to those described previously. Using the experimental data obtained, horizontal velocity and flight time values of $v_x = 4.274$ m/s and $t = 0.314$ s were recorded for Level 2, while values of $v_x = 5.428$ m/s and $t = 0.322$ s were recorded for Level 3. The results for the theoretical horizontal distance for each throwing intensity are shown in the Figure 10. In addition, Table 1 shows the theoretical and experimental horizontal distances obtained, as well as the corresponding error percentages.

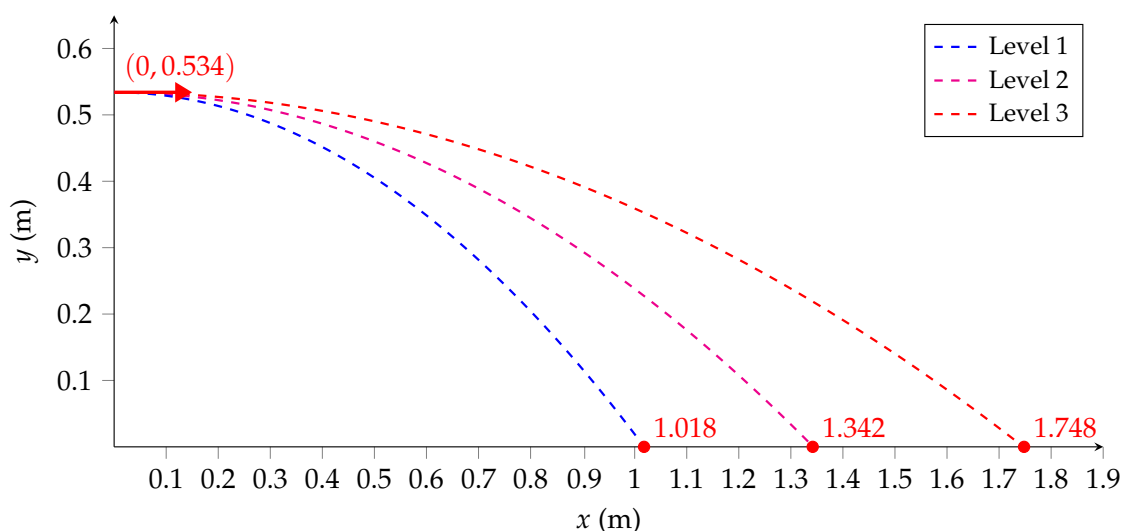


Figure 10. The trajectory, which takes the form of a semi-parabola, is shown for the three available launch intensity levels. The red arrow indicates the direction in which the projectiles are launched from a height of (53.4 ± 0.1) cm above the reference level. The theoretical horizontal distance was determined from the initial velocity and flight time data.

The error associated with the measurements taken by the RL, relative to the range calculated from the initial velocity and time-of-flight data, is less than 5% in all cases, which demonstrates a high degree of reliability in the laboratory, whilst also capturing the error associated with real-world measurements, an essential consideration when experimenting with real equipment.

Table 1. Experimental results for one run of each configuration available in the projectile laboratory.

Experiment	Intensity Level	θ_i	R Calculated	R Measured	% Error
Semi-parabola	1	0°	1.018 m	(1.054 ± 0.002) m	3.536%
	2	0°	1.342 m	(1.382 ± 0.002) m	2.980%
	3	0°	1.748 m	(1.832 ± 0.002) m	4.805%
Full-parabola	1	35°	0.9541 m	(1.021 ± 0.002) m	7.012%
		45°	0.9834 m	(1.090 ± 0.002) m	10.84%
		55°	0.9057 m	(1.012 ± 0.002) m	11.74%
Full-parabola	2	35°	1.673 m	(1.832 ± 0.002) m	9.504%
		45°	1.752 m	(1.938 ± 0.002) m	10.62%
		55°	1.627 m	(1.808 ± 0.002) m	11.12%

3.2.2. Full-Parabola

Experiments in which the projectile followed a complete parabolic trajectory, returning to the same height from which it was launched, were carried out for launch angles of 35° , 45° (maximum range) and 55° . For each angle, two levels of initial velocity were used.

Full-parabola, Intensity level 1 (Low), $\theta_i = 35^\circ$. In this configuration, the recorded initial speed and flight time were $v_i = 3.151$ m/s and $t = 0.396$ s, respectively. Using the value of v_i together with the launch angle $\theta_i = 35^\circ$ in the Equation (2), the result is:

$$R_{1,\text{teo.}} = \frac{(3.151 \text{ m/s})^2 \sin(2(35^\circ))}{9.779 \text{ m/s}^2} = 0.9541 \text{ m} \quad (6)$$

The experimental result obtained for the projectile's horizontal range is:

$$R_{1,\text{exp.}} = (1.021 \pm 0.002) \text{ m} \quad (7)$$

The percentage error of the horizontal range measurement relative to the calculated value is:

$$\%Error_{FC1} = \frac{|0.9541 \text{ m} - 1.021 \text{ m}|}{0.9541 \text{ m}} \cdot 100 = 7.012\% \quad (8)$$

Full-parabola, Intensity level 2 (Medium), $\theta_i = 35^\circ$. Based on the experimental data $v_i = 4.172$ m/s and $t = 0.500$ s, the theoretical range is:

$$R_{2,\text{teo.}} = \frac{(4.172 \text{ m/s})^2 \sin(2(35^\circ))}{9.779 \text{ m/s}^2} = 1.673 \text{ m} \quad (9)$$

The experimental horizontal range of the projectile is:

$$R_{2,\text{exp.}} = (1.832 \pm 0.002) \text{ m} \quad (10)$$

The percentage error of the horizontal range measurement relative to the calculated value is:

$$\%Error_{FC2} = \frac{|1.673 \text{ m} - 1.832 \text{ m}|}{1.673 \text{ m}} \cdot 100 = 9.504\% \quad (11)$$

The remaining cases—Full-parabola, Intensity level 1 (Low), and Intensity level 2 (Medium), for $\theta_i = 45^\circ$ and $\theta_i = 55^\circ$ —were analysed using the same procedure described above. For Level 1, experimental values of $v_x = 3.101$ m/s and $t = 0.497$ s were obtained for $\theta_i = 45^\circ$, and $v_x = 3.070$ m/s and $t = 0.575$ s for $\theta_i = 55^\circ$. For Level 2, the corresponding values were $v_x = 4.139$ m/s and $t = 0.617$ s for $\theta_i = 45^\circ$, and $v_x = 4.114$ m/s and $t = 0.720$ s for $\theta_i = 55^\circ$. The results for the theoretical horizontal distance for each launch intensity and angle are shown in Figure 11, where the theoretical values of R corresponding to 35° (Level 1) and 55° (Level 2) are highlighted. In addition, Table 1 shows the theoretical and experimental horizontal distances obtained, as well as the corresponding error percentages.

For the complete curve, it is found that the error percentages obtained when comparing the calculated range with the measured one range from 7.012% to 11.74%, values greater than those obtained for any semi-parabolic configuration. In all experiments carried out in this laboratory, there are factors that give rise to an associated error, such as the value used for g , which does not necessarily reflect the true value of the physical space in which the experiments were conducted. Another factor to take into account is air resistance, which has a greater effect on projectiles travelling along a longer trajectory, that is, describing a full-parabola. In addition to the above, manual range measurement depends on the user's skill and gives rise to systematic errors inherent to the measurement process, such as parallax errors and minimum reading errors [25,26].

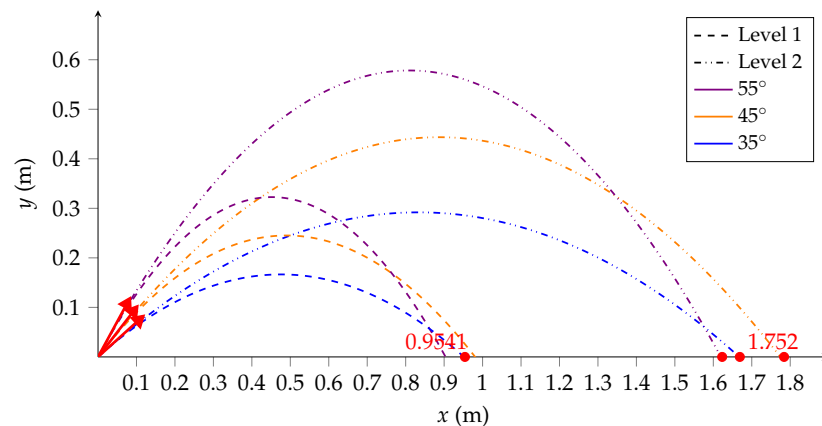


Figure 11. The trajectories corresponding to the full-parabola configuration are shown for the two available launch intensities and three launch angles: 35°, 45°, and 55°. The red arrows indicate the launch directions for each angle. The theoretical horizontal distance was determined using the initial velocity and flight time data. For clarity, the theoretical values of R corresponding to 35° (Level 1) and 55° (Level 2) are highlighted. Level 1 is shown with dashed lines, while Level 2 is shown with dash-dot-dot lines.

4. Conclusions

The RL developed provides an optimised experimental environment for analysing projectile motion across different educational levels. By bringing together launch configuration options and measurement instruments within a single interface, the laboratory enables users to carry out experimental measurements and provides an experience that closely resembles that of a physical laboratory.

The inclusion of interactive elements in the laboratory aims to encourage greater user engagement during the experimental session. The equipment set-up phase, the display of two perspectives (front and top views) of the launch, and the correlation between the audiovisual recordings and the experimental data all contribute to a better understanding of the physical behaviour associated with the motion of projectiles.

The experimental results obtained in the laboratory show error rates ranging from approximately 3% to 11%, with the lowest values corresponding to the semi-parabola configuration and the highest to the full-parabola configuration. These differences between the measured and calculated values can be attributed to factors such as air resistance, the uncertainty associated with manual measurement of the horizontal range, and the inherent variability between replicates. Other variations may arise, for example, depending on how the projectile launcher is positioned or held relative to the measurement table. Such sources of error are characteristic of hands-on experimentation and emphasise the importance of refining the setup to minimise systematic deviations. However, as these are real data with their corresponding experimental error, the laboratory allows the analysis of projectile motion to be approached with the rigour characteristic of experimental practice, which constitutes a substantial advantage over simulations or virtual laboratories.

The experimental uncertainty inherent in the measurements obtained during the laboratory session provides students with the opportunity to apply error propagation techniques as part of their experimental practice.

This article has focused on the design and development of a UL for projectile motion, representing a novel contribution through the integration of real experimental data within a scalable, platform-managed architecture that supports simultaneous access for large student populations. The laboratory also has the potential to support students in overcoming well-documented misconceptions about parabolic motion. However, the pedagogical benefits described here are framed as potential outcomes, as no direct educational assessment

has been conducted with students or instructors. Future work will address this gap by presenting data on student performance, learning outcomes, and quantitative metrics of concurrent access.

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Abbreviations

The following abbreviations are used in this manuscript:

UNED	Universidad Estatal a Distancia
RL	Remote Laboratory
UL	Ultra-concurrent Remote Laboratory

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