A remote laboratory for optical levitation of charged droplets

D. Galan,[1] O. Isaksson,[2] M. Rostedt,[2] J. Enger,[2] D. Hanstorp,[2] and L. de la Torre[1]

[1] Departamento de Informática y Automática, Universidad Nacional de Educación a Distancia (UNED), ES28040, Madrid, Spain

[2] Department of Physics, University of Gothenburg, SE41296, Gothenburg, Sweden

Abstract.

We present a remotely controlled experiment in which liquid droplets are levitated by a vertically aligned focused laser beam. The droplets levitate at the point where the photon pressure of the focused laser beam balances the gravitational force. The size of a trapped droplet can be measured by detecting the diffraction pattern created by the trapping laser light. The charge on the trapped droplet can thereafter be determined by observing its motion when a vertically directed electrical field is applied. This experiment allows a student to study many fundamental physics processes, such as photon pressure, diffraction of light, or the motion of charged particles in electrical fields. The complexity of the experiments and the concept studied make this suitable for advanced studies in physics. The laser power required in the experiment is about 1 W, which is a thousand times greater than the value of 1 mW at which lasers begin to be capable of causing harm to eyes; high voltages are also used. Further, the cost of the equipment is relatively high, which limits its availability to most undergraduate teaching laboratories. It thus constitutes an ideal experiment for remote control.

Keywords: Remote laboratories, optical levitation, lasers, particles in electrical fields, size measurement by diffraction, online experimentation

1. Introduction

Remote laboratories (RLs) offer online remote access to real laboratory equipment for experimental activities. These tools have increased in popularity in higher education with the development and greater accessibility of the Internet [1]. Universities are increasingly offering their students remotely accessible laboratories in order to allow them to spend more time working with laboratory equipment, and hence develop better laboratory skills [2].

It is commonly accepted that RLs have some advantages over their traditional counterparts, such as facilitating handicapped people to perform experimental work, broadening the range of experiments offered to students by sharing RLs between universities and increasing the flexibility in scheduling laboratory work. A final advantage of RLs in general, and of the presented one in particular, is that they offer students training in operating computer-controlled systems, which are at present a natural and important part of research and development, as well as of essentially all other activities in society.

In this work, we present a successful initiative for modernizing teaching using an innovative RL dealing with the optical levitation of charged droplets, illustrating modern concepts in physics with an experiment that is currently being used in a Swedish research laboratory. In the experiment, optical levitation [13] is used to levitate droplets inside a small cell. The cell has similarities with the cell Millikan used in his famous oil drop experiment [14], since an electric field can be used to move the droplet upwards and downwards in the laser beam. The RL presented in this work offers teachers online access to an experiment where concepts of modern physics are introduced without being limited by costs, logistics or safety issues. Students access the RL through a web portal on which they can find documents presenting the theory behind the experiment and manuals describing the experimental setup. By sharing all this material on the Internet, this work opens the door for personal and informal learning in modern concepts of physics that would otherwise require costly and dangerous equipment. The RL enhances formal learning by providing students with more laboratory time working with a spectacular experiment that is not accessible outside research laboratories.

Most RLs in physics available today typically offer classical experiments that have been around for over hundred years. These experiments are primarily suitable for high-school and first-year bachelor students. Göber *et al.* [3] have studied a large number of papers describing RLs. They found that a vast majority of the approximately 120 experiments they found described in physics were in the fields of mechanics or electrodynamics. They recommended in their conclusion that newly developed physics RLs should focus on topics in modern physics (understanding such modern topics as those that rely on physics concepts, advances and/or discoveries made from the 20th century onwards). Another indication of how strongly classical physics dominates RLs can be found on the webpage‡ of the recent RemLabNet project. Here, twenty open-access remote experiments in physics, all created with the Internet School Experimental System (ISES) kit, are presented [4]. Only two of these RLS can be classified as representing modern physics where one is a study of the photoelectric effect and one is an experiment where the Heisenberg uncertainty principle is demonstrated. Moreover, no RL on optical levitation can be found neither in the literature nor on the Internet.

Safety is commonly mentioned as a motivation for creating RLs. However, the only remotely accessible experiments that we could found either on the Internet§ or in the literature [5] that actually benefit from such an advantage are a few examples of RLs involving radioactivity [19]. However, experiments on radioactivity are in general relatively safe due to the low activity of the samples that are usually used for educational

‡ http://www.remlabnet.eu
§ http://www.golabz.eu/lab/radioactivity-lab

purposes. As a matter of fact, the natural background radiation is of the same order as the radiation from many of samples sold for educational purposes. In contrast, the high-power laser used in this work is potentially hazardous. This hazard is eliminated by the remote operation.

The paper is organized as follows: Section 2 presents the experiment, the physics behind it, and the experimental setup; Section 3 describes the user interface for remotely operating the laboratory and Section 4, finally, is the discussion and conclusion.

2. Experimental setup for optical levitation of charged droplets.

Optical levitation is a method for levitating micrometer-sized dielectric objects using laser light. It was first demonstrated by A. Ashkin and J. M. Dziedzic in 1971 [13] who successfully levitated a 20 μm transparent glass sphere. The field of optical manipulation has undergone great development since its inception, with the invention of the optical tweezers being a crucial scientific step [15]. The main advantage of the methods of optical manipulation is that a small object can be trapped and controlled without being in physical contact with its surroundings.

In our experiment, various physical properties of the levitated droplet can be investigated. With the experimental setup, illustrated in Figure 1, students and researchers can measure the size and charge of the droplets and investigate how charged particles move in electric fields.

A detailed description of the experimental set-up can be found in [16], and only a brief description is given here. A DPSS laser (diode pumped solid state), with a maximum power of 2 W is vertically aligned and focused into a glass cell. Droplets are generated using a piezo droplet dispenser and descend down the laser beam until they become trapped just above the focus of the laser. The main purpose of the surrounding cell is to reduce air turbulence which otherwise could push the droplet out of the trap. Trapping occurs when the force of the radiation pressure directed upwards equals the gravitational force acting downwards. A trapped droplet can be seen in Figure 2. Trapping times of up to nine hours have been achieved in our laboratory. The interaction between the droplet and the laser field produces a diffraction pattern, shown in Figure 1. The size of the droplet can be determined using the expression for Fraunhofer diffraction if the distance between the screen and the droplet as well as the scale in the figure is known.

The droplets generated in the system are produced from a liquid consisting of 10% glycerol and 90% water. The water quickly evaporates leaving a glycerol droplet of radius 30 μm in the trap. Droplets generated by the droplet dispenser normally become electrically charged, and most of the times the charge is of negative polarity. The top and the bottom of the trapping cell consist of two electrodes which can be used to apply a vertically directed DC or AC electric field across the droplet. A DC field moves the droplet up or down in the laser beam until it finds a new stable position, while the AC field forces the droplet to oscillate around its equilibrium position. The magnitude of

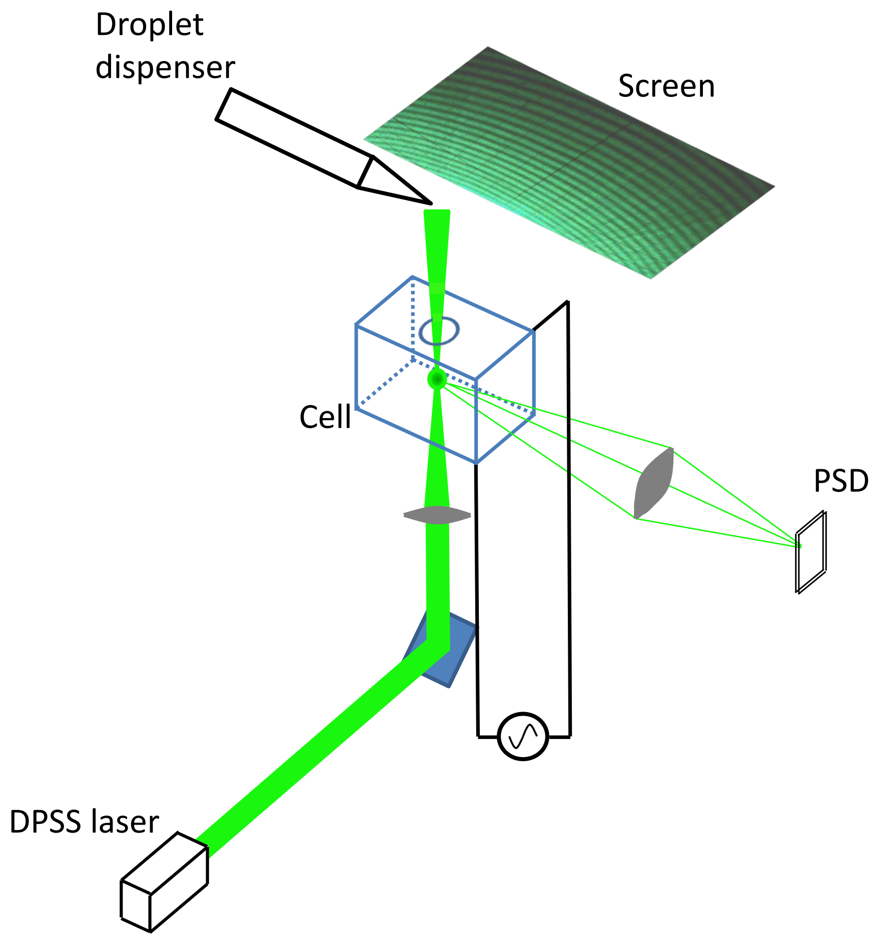

Figure 1. Sketch of the experimental setup. The droplet dispenser produces droplets which are trapped by a focused laser inside a cell. The motion of a trapped droplet is tracked by the PSD (Position Sensitive Detector). The laser is a Diode Pumped Solid State Laser (DPSS), with a maximum power of 2 W and a wavelength of 532 nm.

the oscillations depends on the size of the droplet, its charge, and the strength of the electric field. An image of the droplet projected onto a position-sensitive detector (PSD) allows the user to track the vertical position of the droplet.

The RL presented in this paper can be used to perform numerous demonstrations and experiments:

(i) The photon pressure can be demonstrated by allowing a droplet to fall down from the droplet dispenser towards the focus of the beam. The vertical position of the droplet can then be changed by varying the power of the laser. The droplet's position can be observed either directly with a web-camera or by analyzing the graph produced by the PSD. The students observe, probably for the first time, that a beam of light can generate forces sufficiently large to first levitate and then move macroscopic objects.

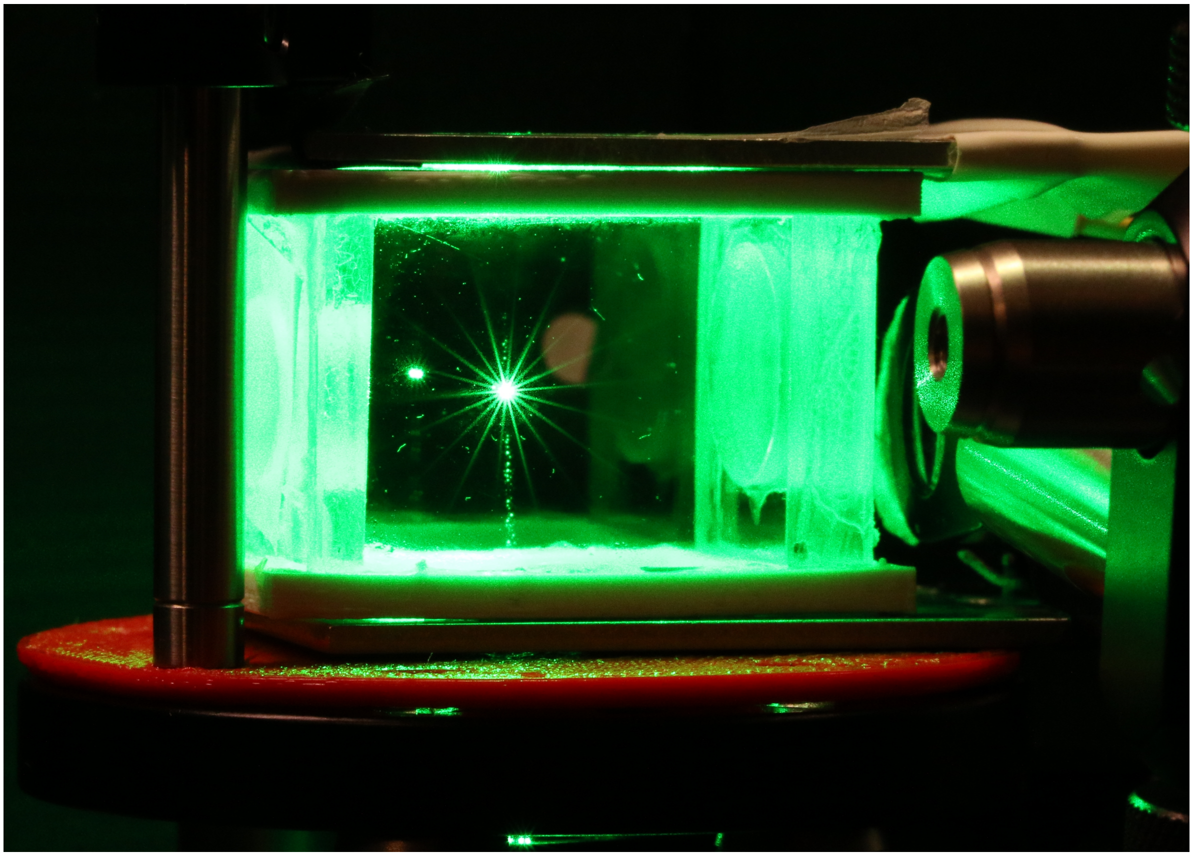

Figure 2. A charged droplet trapped by a vertically aligned laserbeam.

(ii) The size of the droplet can be determined by observing the diffraction pattern created when the laser beam diffracts by the trapped droplet. This pattern is projected onto a screen and observed with an IP camera. In this exercise, the students are able to use the expression for Fraunhofer diffraction of a circular object to determine the size of unknown objects. The vertical distance between the droplet and the screen is 23.5 cm, and the horizontal distance from the droplet to the line marked 1 (see Figure A2) in the diffraction pattern is 40 cm. This information, together with the fact that the wavelength of the laser is 532 nm is sufficient to calculate the size of the droplet. This is described in more detail in Appendix A. The volume of the droplets is 0.1 picoliter, which corresponds to a diameter of 60 μm.

(iii) The position of the droplet can be changed using AC or DC electric fields. If a DC electric field is applied, the droplet moves up or down to a new stable position. If the AC field is used, the droplet will oscillate around its equilibrium position. The polarity of the charge on the droplet is determined by comparing the direction of the electric field with the course of the movement of the droplet. The lower electrode is either positive or negative, and the upper electrode is grounded. A detailed discussion on the behavior of a charged trapped droplet in an electric field can be found in the recent work by Isaksson *et al.* [16].

(iv) It is also possible to use a feedback loop where the position of the droplet is controlled by changing the power of the laser. This is used to keep the droplet at a constant vertical position when an electric field is applied: When the position of the droplet changes due to a change in the applied electric field, the power of the laser will be increased or decreased in order to bring the droplet back to the original position. With this tool, the charge of the droplet can be estimated by lifting it with the DC electric field, and then observe how much the laser power was reduced to bring it back to the original position. The reduction in laser power is then equal to the force from the electric field. This is expressed as a fraction of the weight of the droplet (mg). The size of the droplet can be determined as described above. The mass of the droplet can then be determined since the density of the fluid is known. Hence, the absolute value of the charge can be determined.

3. The remote laboratory

This section provides an overview of the RL. First, the general architecture that supports access for students and researchers to remote laboratories is described; the RL web application is then presented. Finally, the particularities regarding the implementation of the architecture for the droplet optical levitation lab are addressed.

3.1. System architecture

Remote laboratories require that students and researchers are capable of controlling every aspect of the experiment, which usually involves controlling instruments like function generators, lasers, and servomotors. They also need to make online observations of the experiments. For this reason, a system for transmitting real-time images is required. To fulfill these two requirements, we have used a general client-server architecture, which allows the connection between laboratories of diverse nature and web applications. It has been successfully implemented on some previous works [6, 7, 8] and it is shown in Figure 3. This approach is based on three main elements:

(i) *EjsS (Easy Java/JavaScript Simulations).* This is an authoring tool that facilitates the creation of computer simulations and laboratories [9]. The large amount of free EjsS applications that can be found in the open source physics (OSP) repository [10] is a reliable indicator of the success of EjsS. In our Optical Levitation of Charged Droplets RL, EjsS is used to implement an application that serves as a user interface on the client side. The application allows students and researchers to interact with the set-up and instrumentation to carry out experiments and record experimental data.

(ii) *LabVIEW (Laboratory Virtual Instrument Engineering Workbench).* The server is a PC equipped with LabVIEW VI (Virtual Instrument) and a data acquisition card (DAQ). The primary functions of this PC are to control the experiment and implement safety measures to avoid damaging the experiment in case of accidents or malicious users.

(iii) *JIL server*. This is a middleware program running on the server side that enables users to connect the client-side EjsS RL application to the LabVIEW VI in the laboratory [11].

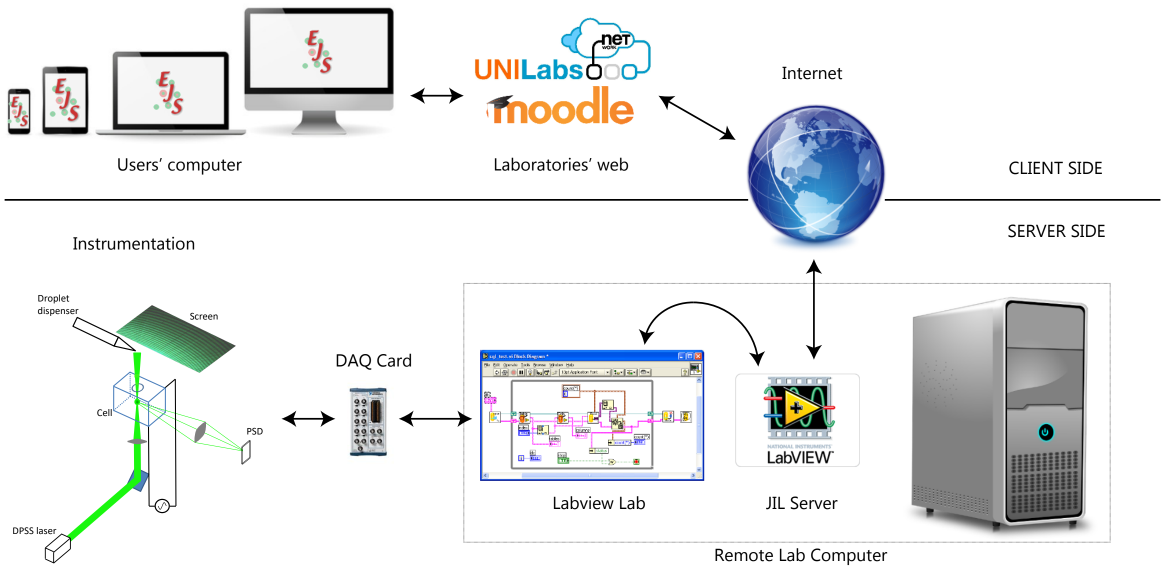

Figure 3. Architecture of remote laboratory experiments. Users can access the laboratory using the RL application through the UNILabs webpage. The server-side includes the JIL server to grant the communication and the LabVIEW VI to interact with the instrumentation.

3.2. The RL application

An intuitive application that allows the experimenter to perform the same tasks as if they were on site in the laboratory has been created. Since one of the purposes of the RL is to be used by both students and researchers, it was necessary for the application to be able to carry out all the tasks that the instrumentation allows without any technical limitations. Moreover, the RL application is connected with the same LabVIEW VI that the researchers use to perform their experimentation tasks on site. In this way, we ensure that any changes in the setup or any new functionality added, can be quickly and easily included in the RL application.

The RL application for conducting experiments has been designed using EjsS. It has been developed in JavaScript and can, therefore, be deployed in any standard web browser. The RL application is available online from an open course at the University Network of Interactive Laboratories (UNILabs: `http://unilabs.dia.uned.es`) web portal [12], supported by the Moodle Learning Management System.

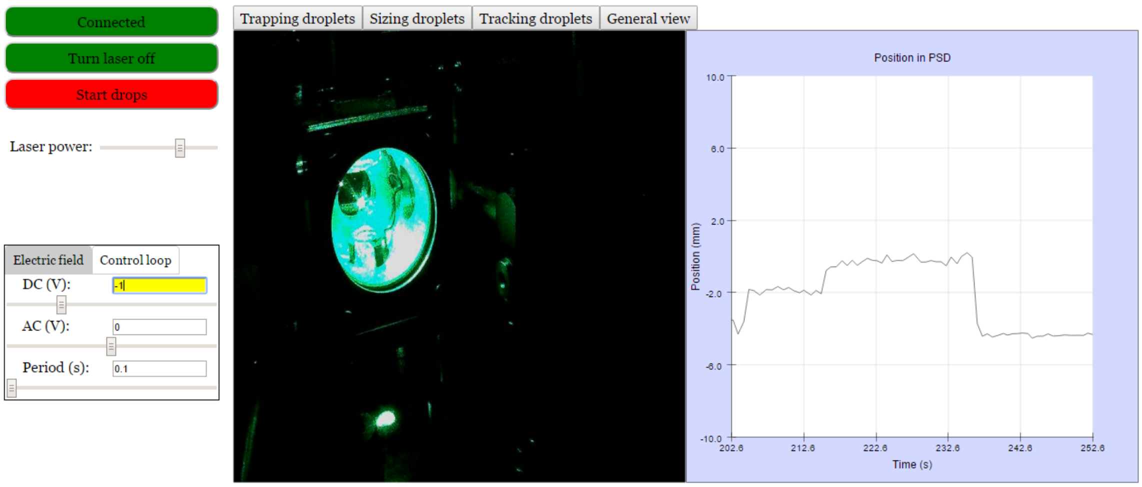

Figure 4. Remote laboratory graphic user interface. The tracking droplets camera can be seen in the middle of the figure. On the right side, the plot represents the position of the droplet as a function of time. It is possible to see a step in the graph of the droplet position due to a user change in the electric field.

Figure 4 shows two images of the remote laboratory application's graphical user interface (GUI). The interface is divided into two main areas. The left side is used for controlling and interacting with the laboratory devices to perform the experiments. In this part, buttons to turn the laser and the droplet dispenser on and off are provided, as are sliders to change the intensity of the laser and the parameters of the electric field (DC or AC mode, electric field voltage and, when AC mode is selected, the period of the wave). Finally, there is a check-box to activate and deactivate a feedback system for fixing the location of the trapped droplet, and a slider to select the desired position for the feedback system. The right side is used to give visual feedback to the users using videos and graphs. This part has four tabs presenting the following information:

(i) *Trapping droplets* offers a close view of the cell; here it can be observed how a droplet ejected from the dispenser is trapped by the focused laser beam.

(ii) *Sizing droplets* shows the diffraction pattern created by the droplet.

(iii) *Tracking droplets* contains a graph plotting the vertical position of the droplet as a function of time.

(iv) *General view* gives a general picture of the experimental setup.

Appendix A presents a description of the procedure for using the RL application to perform the experiments presented in Section 2.

3.3. Specific implementation details for the optical levitation remote lab

As soon as the user opens the RL application and presses the button "Connect", the JIL server runs the LabVIEW VI, which automatically switches on the instrumentation. In the same way, when a disconnection occurs, either because the user finishes the work or

Table 1. Defined variables linked between the RL application and the LabVIEW VI

RL client app	LabVIEW VI	Type
laserPower	Laser Current	Input (double)
enableLaser	Laser Remote Enable	Input (boolean)
setpointLabv	Position Setpoint	Input (double)
eDCvolts	EField DC Control	Input (double)
eACvolts	EField AC Control	Input (double)
periodLabv	EField Period (s)	Input (double)
controlDrops	Drops	Input (boolean)
controlLoop	Run Control loop	Input (boolean)
t	t	Output (double)
psdPos	PSDPosition	Output (double)

because of a connection failure, the instrumentation is switched off. In this way, safety is guaranteed because the laser and electric fields are never left on without supervision. From the moment the RL client application connects to the remote laboratory, it starts receiving the server values “t” (time) and “PSDPosition” (position of the drop obtained with the PSD) every 100 milliseconds. The values received from the server are assigned to the local variables “t” and “psdPos”, which are used by the RL client application to plot the graph displayed in Figure 4. Users can click the button “Turn laser on” to switch on the laser at any time. This action will cause the local variable “enableLaser” to be set to “true”. That value is then transmitted to the server, changing the value of the VI variable “Laser Remote Enable”, which will finally turn the laser on. In the same way, the user can modify the laser power with its corresponding button. When pressed, “laserpower” changes its value and it is sent to the server, writing such value in the variable “Laser Current”. Given that high power of the laser for an extended period pose a risk, the application has been limited so it cannot exceed 80% of the maximum generated power. Similarly, changes from the RL client application in any other linked variables will be transmitted to the server in the same way. Table 1 shows the variables we had to link to this particular lab to make possible all the experimentation activities described in Section 2.

4. Learning outcomes

According to Lundgren *et al.* [20] the experience for students using remote laboratories is similar to doing a traditional laboratory exercise. Conclusions were made after analyzing logbooks of more than 200 students. The students seemed to experience the remote lab as real, not as an artificial simulation.

The basic idea of making optical levitation a remote laboratory is to provide the students with the possibility to observe this experiment in real time. In the most basic use of this RL, students can turn the laser and the droplet dispenser, and observe that light actually can be used to levitate matter. Together with the electric field to determine polarity, it gives a good experience also for non-physics students.

As the level of experience of the students increases, the exercise can be made more challenging, by for example determining the size of the droplets.

A group of students studying physics at the IB-Diploma Programme in Halmstad, Sweden, tested the remote laboratory by performing the following:

(i) Start the laser.

(ii) Initiate the production of droplets and wait until one is trapped.

(iii) Determine the polarity of the charge of the droplet.

(iv) Calculate the size of the droplet.

After the remote laboratory exercise, the students were asked to fill in a questionnaire about their experiences. The questionnaire contained questions about the experimental set-up, their measurements/experiences, physical concepts and benefits and disadvantages of remotely controlled laboratories in general and the optical levitation experiment in particular.

The students were all really amazed by the ability of light to lift and trap objects. The procedure, presented in Appendix A.1 was used to calculate the size of the droplets. The results they obtained were closed the actual size of 60 μm.

The benefits of remotely controlled laboratories mentioned by the students were that it goes much faster to do the exercise since the equipment is already in place. The safety issues with powerful lasers were also mentioned. One disadvantage that was mentioned was it would be hard to repair the system if its function fails during the experiment. Several students also said that there is a need for investing in better cameras.

The last question on the questionnaire was: Is there anything else you want to add about the lab? Examples of answers were: ”It was, in conclusion, very interesting”, ”Very enjoyable”, ”No” and ”Interesting concept”.

5. Conclusions

In this paper, an experimental set-up has been presented for carrying out modern physics experiments on an optically levitated droplet. The remote system allows access to the experimental setup to students and researchers all over the world and guarantees the safety of users, as they do not need to be in the presence of the high-power laser or the high voltages required for the experiment. In addition, the automation of the set-up allows users to interact with the instrumentation in a straightforward way, by sending high-level commands via a computer. This makes it possible to bring modern physics experiments—in this case, an experiment on optical levitation—to those who cannot afford the rather expensive equipment required.

The experimental system presented here for educational purposes is also used in various research projects. For instance, the set-up has been used to study the collision of micrometer-sized droplets using high-speed cameras [17]. Further, the same experimental platform has been employed to construct a sensitive way to track the position of particles using a Sagnac interferometer [18].

Future plans for the laboratory include trapping in a vacuum cell, which will allow droplets to be studied under different pressures. Preliminary studies have shown a decrease in the delay between the motion of the droplet after an AC electric field has been applied. Finally, the remote lab will soon include an option to alter the charge on the particles by exposing them to either a radioactive source or UV light. This will be performed in situ so that the user will be able to observe a decrease in the amplitude of the oscillations of the trapped droplet when the AC electric field is applied.

Acknowledgments

This work has been supported by the Spanish Ministry of Economy and Competitiveness under project CICYT DPI2014-55932-C2-2-R, the Swedish Research Council, the Carl Tryggers Foundation for Scientific Research and Sannarpsgymnasiet, Halmstad. Thanks also to Niels Giesselmann for assistance in the laboratory.

References

[1] Heradio R, de la Torre L, Galan D, Cabrerizo F J, Herrera-Viedma E and Dormido S 2016 Virtual and remote labs in education: a bibliometric analysis *Computers & Education* **98** 14–38

[2] de la Torre L, Sanchez J P and Dormido S 2016 What remote labs can do for you *Physics Today* **69** 48–53

[3] Gröber S, Eckert B and Jodl H J 2013 A new medium for physics teaching: results of a worldwide study of remotely controlled laboratories (rcls) *European Journal of Physics* **35** 1–4

[4] Lustig F, Dvorak J, Kuriscak P and Brom P 2016 Open modular hardware and software kit for creations of remote experiments accessible from pc and mobile devices *International Journal of Online Engineering* **12** 30–36

[5] Jona K and Vondracek M 2013 A remote radioactivity experiment *Physics Teacher* **51** 25–27

[6] de la Torre L, Guinaldo M, Heradio R and Dormido S 2015 The ball and beam system: A case study of virtual and remote lab enhancement with moodle *IEEE Transactions on Industrial Informatics* **11** 934–945 ISSN 1551-3203

[7] Bermudez-Ortega J, Besada-Portas E, Lopez-Orozco J, Bonache-Seco J and de la Cruz J 2015 Remote web-based control laboratory for mobile devices based on ejss, raspberry pi and node.js *3rd IFAC Workshop on Internet Based Control Education, IFAC-PapersOnLine* vol 48 (Brescia, Italy) pp 158–163

[8] Esquembre F 2015 Facilitating the creation of virtual and remote laboratories for science and engineering education *3rd IFAC Workshop on Internet Based Control Education, IFAC-PapersOnLine* vol 48 pp 49–58

[9] Christian W and Esquembre F 2007 Modeling physics with easy java simulations *The Physics Teacher* **45** 475–480

[10] Christian W, Esquembre F and Barbato L 2011 Open source physics *Science* **334** 1077–1078

[11] Chaos D, Chacon J, Lopez-Orozco J A and Dormido S 2013 Virtual and remote robotic laboratory using ejs, matlab and labview *Sensors* **13** 2595–2612 ISSN 1424-8220

[12] de la Torre L, Sanchez J P, Heradio R, Carreras C, Yuste M, Sanchez J and Dormido S 2012

Unedlabs - an example of ejs labs integration into moodle *World Conference on Physics Education*

[13] Ashkin A and Dziedzic J 1971 Optical levitation by radiation pressure *Applied Physics Letters* **19** 283–285

[14] Millikan R 1910 A New Modification of the Cloud Method of Determining the Elementary Electrical Charge, and the Most Probable Value of that Charge *Philosophical Magazine* **19** 209–228

[15] Ashkin A, Dziedzic J M, Bjorkholm J E and Chu S 1986 Observation of a single-beam gradient force optical trap for dielectric particles. *Optics Letters* **11** 288–290 URL `http://www.ncbi.nlm.nih.gov/pubmed/19730608`

[16] Isaksson O, Karlsteen M, Rostedt M and Hanstorp D 2018 An optical levitation system for a physics teaching laboratory, accepted for publication in american journal of physics (2018) **8810** 88–100

[17] Ivanov M, Chang K, Galinskiy I, Mehlig B and Hanstorp D 2017 Optical manipulation for studies of collisional dynamics of micron-sized droplets under gravity *Optics Express* **25** 1391–1404

[18] Galinskiy I, Isaksson O, Salgado I R, Hautefeuille M, Mehlig B and Hanstorp D 2015 Measurement of particle motion in optical tweezers embedded in a sagnac interferometer *Optics express* **23** 27071–27084

[19] Jona K and Vondracek M 2013 A remote radioactivity experiment *The Physics Teacher* **51** 25–27

[20] Lundgren P, Jeppson K and Ingerman Å 2006 Lab on the web-looking at different ways of experiencing electronic experiments *International journal of engineering education* **22** 308–314

Appendix A. Experiments with the remote laboratory

To facilitate understanding of the RL's functionality, the most common experimental procedures are explained in this appendix.

(i) Trapping a droplet:

  (a) Click on the *Connect* button to start receiving the live video stream from the webcams and to initialize the instrumentation.
  (b) Select the *Trapping Droplets* tab to observe the pipette.
  (c) Initialize the laser connection by clicking the *Turn laser on* button. Laser initialization is performed separately from that of the other instruments for safety reasons.
  (d) Once the laser has been initialized and it is safe to begin the experiment, set the laser power to 65%. Use the *Laser power* slider to achieve this. Wait until the green light illuminating the pipette can be seen.
  (e) Activate the droplet dispenser by pressing the *Start Drops* button. The droplets will begin to fall from the pipette towards the focal point of the laser beam. The droplet dispenser can be deactivated once the droplet is captured. Alternatively, it is possible to obtain a larger droplet by trapping several of them and allowing them to coalesce in the trap.

(ii) Determining the mass of a droplet:

  (a) Change the view to *Size Droplets* by clicking on the corresponding tab. The diffraction pattern generated by the droplet will be visible.
  (b) Study the diffraction pattern to obtain an approximate measure of the size of the droplet. This procedure is explained in Appendix A.1.
  (c) The density ρ of glycerol is 1.26 g/cm^3.

(iii) Studying the position of a droplet:

  (a) Select the *Tracking Droplets* view. This consists of a front view of the pipette with the levitated droplet in the inset, and a plot with the position of the droplet (measured by a PSD) in function of the time.
  (b) Modify the laser power to 55% using the *Laser power* slider.
  (c) Study how the droplet position changes.
  (d) Repeat the two previous steps with different laser power values to obtain the relation between the power of the laser and the position of the droplet.

(iv) Stabilizing the position of a droplet:

  (a) Select the *Tracking Droplets* view.
  (b) Select the *Control loop* tab situated on the lower left-hand side.
  (c) Use the *Position set-point (mm)* slider to choose the desired position for the droplet.
  (d) Activate the control loop by selecting the check-box *Run the control loop.* From this moment until the deactivation of the control loop, the laser power will be

automatically controlled to fix the droplet at the position determined by the set-point value.

(v) Determining the polarity of the charge on the droplet:
   (a) Set the voltage to 100 V DC.
   (b) Note the direction of the droplet's movement
   (c) If the droplet moves downward, its charge is negative; if it moves upward, the charge is positive.
   (d) Verify your conclusion by applying -100 V.

Appendix A.1. Droplet sizing procedure

The Fraunhofer diffraction pattern created by the particle is used to measure its size. The pattern is projected onto a screen and filmed by one of the IP cameras. An example of a diffraction pattern obtained is shown in Figure A1.

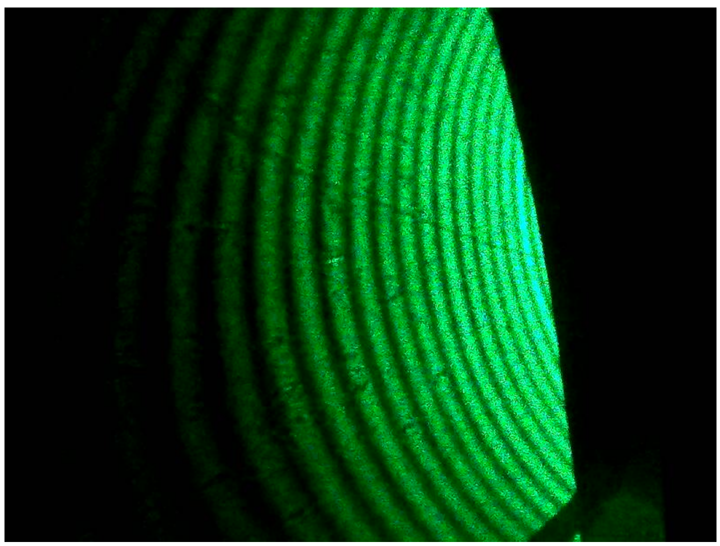

Figure A1. Diffraction pattern from a trapped droplet.

The size of the droplet is determined by choosing the *Sizing droplets* tab in the EjsS interface. The diffraction pattern of the trapped droplet is shown. The figure contains some of lines that are spaced one centimeter apart. The horizontal distance from the trap to the line marked as 1 is 40 cm. First, identify the center of the two light minima in the picture and count the number of minima between them (Δn). As an example: The first minima used for the calculations is 1, and the next is 4, giving $\Delta n = 3$.

Measure the distance from line 1 to the first minima and add 40 cm. This is a_1. Continue by measuring the distance from line 1 to the second minima of choice, add 40 cm, and call this a_2.

The distance x in Fig A2 is fixed at 23.5 cm.

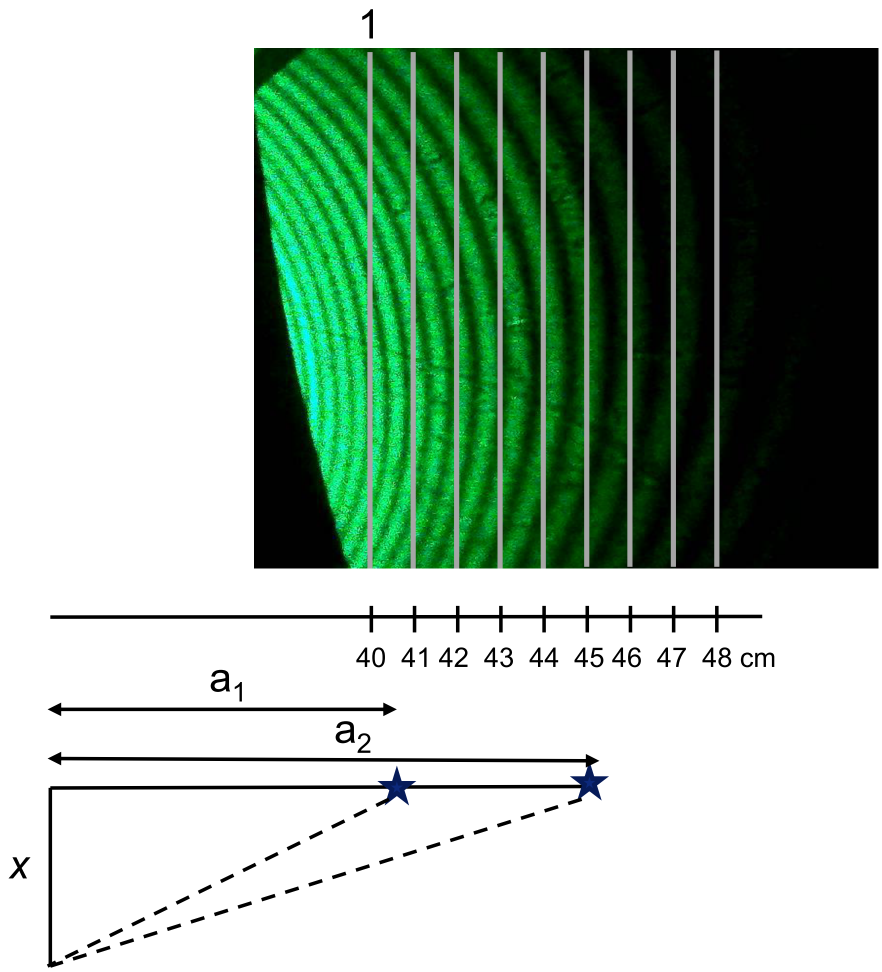

Figure A2. How the diffraction pattern is used to determine the size of the trapped droplet. The two stars in the drawing relate to two minima in the diffraction pattern. The horizontal distance between line 1 and the trapping laser is 40 cm.

The size of the droplet can then be calculated from the expression

$$d = \frac{\Delta n \cdot \lambda}{\frac{a_2}{\sqrt{x^2+a_2^2}} - \frac{a_1}{\sqrt{x^2+a_1^2}}}, \tag{A.1}$$

where d is the diameter of the droplet and λ is the wavelength of the laser (λ=532 nm). The size of the trapped droplets can also be measured by the phase difference between the position of the droplet and the driving AC fields, as described in the paper by Isaksson *et al.* [16].