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IMPLEMENTATION OF NATURAL EXPERIMENTS IN PHYSICS USING COMPUTER VISION

Abstract: Laboratory experiments in physics are a fundamental basis for studying physical phenomena occurring in nature and a methodological tool that provides visibility of the learning process and conducting experiments is important for the formation of students' scientific worldview, deep understanding of physical laws and increasing interest in the study of physics. Existing in universities and schools, in addition to traditional ones, modern tools, technologies and approaches, such as virtual reality, augmented reality, computer modelling, online laboratories, virtual laboratory and others, are additional tools for improving the quality of the learning process and teaching techniques, which do not replace full-scale experiments, but only supplement them. In our opinion, for better learning, laboratory installations in physics are needed, with the help of which students can carry out real-life experiments and can broadcast them using innovative computer technologies for distance learning. To implement

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this task, we reviewed and analysed existing laboratory installations, identified their advantages and disadvantages, and then designed and developed alternative digital experimental set-ups for studying physics phenomena in laboratory conditions of educational institutions based on computer vision technology and presented the results of the study in this article. In carrying out the research tasks, effective methods of conducting scientific research were used, such as theoretical substantiation of the issue, experimental testing of the developed hardware and software systems and computer final processing of experimental data. In summary, the research described in the paper presents an innovative mechanism for integrating object tracking based on computer vision to improve the quality of measurements and new ways of conducting physics experiments. The mechanical laboratory complexes we have developed consist of hardware and software parts. The software part consists of server and client parts. The hardware consists of the main part - the scene, where the physical process takes place, i.e. where a physical object is located, such as a mathematical pendulum, an inclined plane, etc., with the help of which many physical phenomena and processes in mechanics can be demonstrated, and an additional part where a microcomputer and a camera are located. The operating principle of the laboratory installation is based on the use of computer vision technology, i.e. a system for monitoring the ongoing physical process, consisting of a digital camera for image processing, object identification and data export, and a microcomputer for processing experimental data. The use of the experimental installations in the process of teaching physics is a new model of teaching with a promising future in secondary and higher education, and the installations themselves will become tools for offline and online learning, due to the use of computer vision technology, revealing new opportunities and approaches to teaching.

Keywords: physical experiment; laboratory installation; computer vision; secondary education; higher education; information and communication technologies; computer technologies.

Introduction

To achieve the goals of providing quality education and promoting lifelong learning, young people with skills and interest in science as their future professional field are needed [1], [2]. Today, the process of learning science is a very important matter for modern students, which is necessary for them to participate as informed and active members of society, as well as to develop scientific thinking and skills for decision-making based on scientific facts [3]. Applying science to our daily lives requires practice, and real physical or digital laboratories are required to implement it. Laboratories existing in universities and schools help students instill a great interest in science, participate in research activities [2], develop knowledge based on experiment and a combination of theory and experiment, as well as develop their skills, abilities and competencies. Therefore, laboratory experiments for the study of natural and technical sciences, as an important element of the educational process, are valuable and generally recognized.

The physics course is usually studied in all engineering and technical specialties of universities during the first year of study at the university and, through experiment reflects scientific methods and means of knowing objects and phenomena of the surrounding world. A physical experiment has many functions, for example, it is a means of studying phenomena of the surrounding world, it connects theory with practice, reveals the goals of studying physics; it is a methodological tool that ensures the clarity of learning, developing interest in physics; a way of organizing independent, creative and research activities of students. The process of conducting an experiment and its observation is of great importance for conducting scientific research in physics and equipping students with practical skills. The study of physical phenomena based on a laboratory experiment contributes to the formation of scientific thinking in students, a strong assimilation of physical laws, and an increase in interest in studying physics.

Our experience in teaching physics at school and university shows that when teaching physics there are a number of problems, such as a lack of teaching laboratories, wear and tear and rising prices for technical equipment, difficulties in planning and conducting laboratory classes in existing physics laboratories, non-standard moments related to natural disasters, such as a pandemic and their impact on the educational process, the lack of laboratory facilities that demonstrate real physical phenomena and processes in laboratory conditions and transform them, the influence of information technology and the Internet, etc.

Since laboratory work is an important pedagogical form of organizing the educational process for acquiring competencies in the field of natural science education and helps students understand the theory through experimentation [3], it indicates the need to solve problems through the development of alternative modern equipment for physics based on innovative computer technologies and effective educational material for it.

Literature review

Education is a developing area of human society throughout the world and is associated with the constant development of teaching methods and tools based on the use of innovative computer technologies. All this radically changes the content of the role of physical laboratories, their forms, formats and tools for experiments, for example, virtual and remote laboratories, virtual and augmented reality, interactive video and games, and have a positive impact on the knowledge, skills and abilities of students.

For example, virtual reality is one of the strategies for teaching physics, and an alternative to the traditional computer-generated physics laboratory, and its use in relation to a physics experiment is associated with the creation of a virtual laboratory. Today, there are many pilot studies under way on the use of virtual laboratories for practical teaching of physics in secondary schools and higher educational institutions [3]. Some researchers believe that this strategy is an ideal approach for teaching understanding of physics and makes it possible to illustrate scientific physical phenomena through virtual classes using computer simulations [3]; it effectively supports students' remote laboratory practice [4]; allows students to study independently, i.e. prefer communication with computers [5]; improves students' conceptual understanding skills [6]; develops the ability to solve problems [7]; increases the creative abilities of students [8]; is a resource for improving the learning process [9]. Virtual labs are a specific approach to hands-on laboratory experiences using computer simulations that aim to present views and ways of working that are similar to their physical counterparts; used to attract the attention of students and maintain their motivation, provide additional benefits, such as support for distance learning [3]; are able to improve the quality of learning and develop students' meta cognitive skills [10].

Other researchers have created virtual laboratories to support and provide students with additional work experience to the existing physical laboratory, which students find very informative and useful [3]; noting their availability on mobile devices and the Internet, low flexibility, expensive cost, but profitability and effectiveness for teaching physics in secondary schools [11]. Virtual laboratories are created and used for the purpose of studying and understanding many topics of a physics course, to provide real-time visualization [12], taking into account the requirements of the educational system of Kazakhstan, the shortcomings of existing solutions [13]; allowing users to experience visual sensations and experience of conducting experiments, observing the state of the system at any time in real time.

Thus, the virtual laboratory becomes one of the important components of the electronic learning environment, especially for the disciplines of scientific and technical education, which completely or at certain stages replaces the real object, but there is no substantive clarity. Also, a virtual laboratory reduces the time for conducting an experiment, but at the same time does not allow acquiring skills in working with real equipment. At the same time, it allows focusing students' attention on key aspects of the object being studied, although the virtual model, as a rule, has a simplified appearance. The positive point is that it ensures the safety of the experiment, but at the same time it has many settings available. It should be noted that a virtual laboratory is economically feasible for implementation, but requires special equipment, a stable Internet connection, additional costs for training teachers, as well as the development of individual content in accordance with the educational program.

The next important educational tool for conducting experiments is computer simulation, where a system consisting of a model and a computer replaces a real experimental set-up. In science education, the effectiveness of using laboratory simulations to teach physics is higher than the more traditional approach (face-to-face teaching) [14]; an advanced and pedagogical tool [15], a main part of the scientific way of acquiring knowledge [16]; mathematical models of physical phenomena and processes for students to understand. Other researchers reviewed and analysed some aspects of computer simulations. They believe that time gained by experimenting with accurate computer simulations could be used to engage students in analytical, creative learning. This study supports a wider use of computer simulations as learning tools in laboratory courses [17]. The use of computer simulation is significant for enriching the teaching process, for example, for deep understanding of the lecture, its scientific subjects [3], while providing a high level of interaction, active involvement and participation, immediate feedback and repetitive practice tasks. The use of computer modelling leads to a favourable attitude of students towards science, according to other researchers [18].

Thus, computer simulations are a tool that supports the simulation environment but is not capable of detecting new phenomena without confirmation in real conditions and experiments. Computer modelling studies models in theory but does not have confirmation and evidence of natural phenomena in real conditions.

Today, teachers and students are attracted by augmented reality technology (AR, Augmented reality). This technology, using various devices such as smart phones, tablets, AR glasses and lenses, creates a feeling of the virtual and physical world, visualization of invisible educational content [19], interactive exploration of phenomena as a complement to a full-scale experiment when teaching physics. At the same time, augmented reality technology requires available bandwidth, additional equipment, can distract students from reality, etc.

The next popular technology is virtual reality (VR) technology, which allows virtual expansion of reality, better perception and understanding of the surrounding reality. VR technology is a practical tool and catalyst for distance and face-to-face learning [20], making the learning process convenient for the teacher and students. On the other hand, the use of this technology requires high-quality equipment and virtual reality applications, has limitations in the availability of content, and lack of interaction with real physical objects. Therefore, VR technology is more suitable to complement or enhance traditional teaching technology.

When studying physics, many experiments are carried out, where it is often necessary to track the movements of objects and make repeated measurements. To effectively solve this problem, there is a simple mechanism for integrating tracking based on computer vision. Computer Vision (CV) technology automates the processes of analysis and recognition of observed objects and data, creates systems that independently recognize objects and classify them, accelerates the processing of visual information and performs a number of other tasks.

Another pedagogical technology in education that has great potential for conducting experiments in physics is the use of an online laboratory. The online laboratory is an example of the union of a practical approach to teaching and information technology (IT) [4], an effective tool for improving the quality of teaching [3], teaching methods, learning experience and enhancing participation and motivation, a useful tool for ensuring lifelong learning for distance learning [21], which does not replace full-scale experiments, but only complements them. The use of an online laboratory is an integrated e-learning strategy where experiments are carried out remotely via the Internet, without equipment or programming. Since effective learning requires a simultaneous combination of traditional and electronic teaching methods, online laboratories create a more constructive and active learning environment and improve the quality of student learning [22].

Today, an effective approach is also a properly organized combination of various computer technologies and digital tools, which make it possible to effectively conduct a variety of laboratory work in physics for full-time and distance learning. For example, the study by some researchers provides an analysis of the capabilities of modern digital teaching tools for effective distance conduct of laboratory classes in physics. Other scientists who have conducted research [32] in the field of teaching methodology point to the great influence of digital devices on improving the academic performance of students, proposes a teaching method for conducting physics experiments by programming a mobile robot [23]. Another digital tool is the smart phone, which can be integrated into the learning environment due to the capabilities of high-speed Internet access, large storage capacity, built-in multifunctional sensors and integrated modern smart applications and is effectively mobile. The work of Corina Radu and others [24] examined physics experiments carried out using smart phones outside a physics laboratory using the free Phyphox application. Other researchers such as Pablo Martín-Ramos, Mário S.M.N.F. Gomes, Manuela Ramos Silva [25], also uses a smart phone as an excellent technological platform with sensors for video tracking of a physical experiment. But at the same time, the disadvantage of these methods of demonstrating a physical phenomenon is the lack of a user graphical interface and manual measurement.

So, our review of research and work regarding existing technologies for conducting physical experiment showed that the use of existing approaches, technologies and modern digital devices in the educational process improves understanding of the laws of physics only in combination with natural experiments.

Purpose and objectives of the study

In our research, we were interested in solving existing problems when conducting full-scale physical experiments, in transforming and integrating experiments using computer technology into the educational process of schools and universities. In our opinion, full-scale laboratory work helps real perception of physical phenomena and processes, and the capabilities of modern technologies help overcome the limitations of physical real laboratories for distance learning. Therefore, the goal of our research was to develop digital experimental installations for studying physics phenomena in the laboratory conditions of educational institutions based on innovative computer technologies. These installations will become an alternative solution, one of the most attractive and powerful tools for teaching physics for both higher and secondary education. Their peculiarity is that with their help, real experiments are automatically controlled thanks to electronic elements, and measurement and calculation of physical quantities - with the help of modern computer technologies. The use of laboratory installations will increase the level of observation, perception and understanding of physical processes, due to their full visualization and high accuracy of measurements of physical quantities. Moreover, students will have the opportunity to clearly see and apply robotic elements, computer vision and neural networks when studying a physical process and solving engineering problems. In our opinion, they will become effective tools for solving problems related to the study of topics and theoretical concepts of physics, requiring visualization and modelling of physical processes or phenomena, fast and accurate measurement of their parameters, and broadcasting of the experiment in both face-to-face and distance learning formats.

To achieve this goal, a number of tasks were set, such as:

- determination of physical processes in mechanics, fast-flowing and difficult to reproduce in reality in educational laboratories;
- organizing and writing technical specifications for the development of digital experimental installations that allow organizing real educational experimental measurements;
- development of a library of system modules necessary for processing experimental data obtained in the process of using computer vision;
- design and creation of models of key elements of software and hardware systems;
- creation of software interface windows as a web application to control the experiment process;
- development of a methodology for the use of laboratory complexes in the educational process in order to demonstrate full-scale physical processes in mechanics;
- development of complete methodological support for the process of performing research and laboratory work, implemented using software and hardware systems;
- development of pilot industrial samples of laboratory installations;
- registration of copyright for developed educational and laboratory installations.

To achieve this goal, a group of researchers, took part in the annual competition for grant funding of scientific and scientific-technical projects in the scientific direction "Artificial Intelligence and Information Technologies: Smart Technologies in Scientific and Electronic Educational Processes", held by the Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan. The project we presented, "Development of digital experimental installations for studying physics phenomena in laboratory conditions of educational institutions using modern computer technologies," was approved and supported by the Ministry of Education and Science of the Republic of Kazakhstan, and Seifullin University became an experimental platform for its implementation.

Methods and Materials

To accomplish the research objectives, the most effective methods of conducting scientific research have been introduced, starting from theoretical ones, such as a review and analysis of scientific and technical literature on the problem under study, to empirical ones, organizing and conducting the experimental part of it. The theoretical provisions of the study are focused on analysing the potential of using computer technology to recognize objects involved in spatio-temporal processes, such as mechanical movements. Then, the conclusions based on the results of the theoretical stage of the project will undergo experimental confirmation and final processing of the data obtained at the experimental stage.

Thus, in the process of implementing this project, general scientific methods were used, such as theoretical substantiation of the issue, experimental testing of the developed hardware and software systems, computer final processing of the experimental data.

To develop a hardware and software complex, and then conduct experimental research and measurements, video processing methods and computer vision algorithms, the corresponding equipment, radio components and consumables were used.

Results

Our research presents an innovative mechanism for integrating computer vision-based object tracking to improve the accuracy and quality of measurements and new approaches of conducting physics experiments of hardware (module) and software. The software part consists of a server part (server) and a client part (client). The hardware consists of the main part - the scene, where the physical process takes place, i.e. where a physical object is located, like a mathematical pendulum, inclined plane, etc., i.e. demonstration physical bodies, with the help of which you can demonstrate many physical phenomena and processes in mechanics, and an additional part where the Raspberry Pi microcomputer and camera are located.

The server part of the complex was created based on the Django framework of the Python programming language. The client part of the complex is implemented in the form of a web page using technologies such as HTML, CSS, JS, JQuery and Jinja. The structure of the client part is represented by the main page, and it is from the laboratory and demonstration classes. The main page, shown in Figure 1, does the preparatory work for completing a demonstration or laboratory lesson.

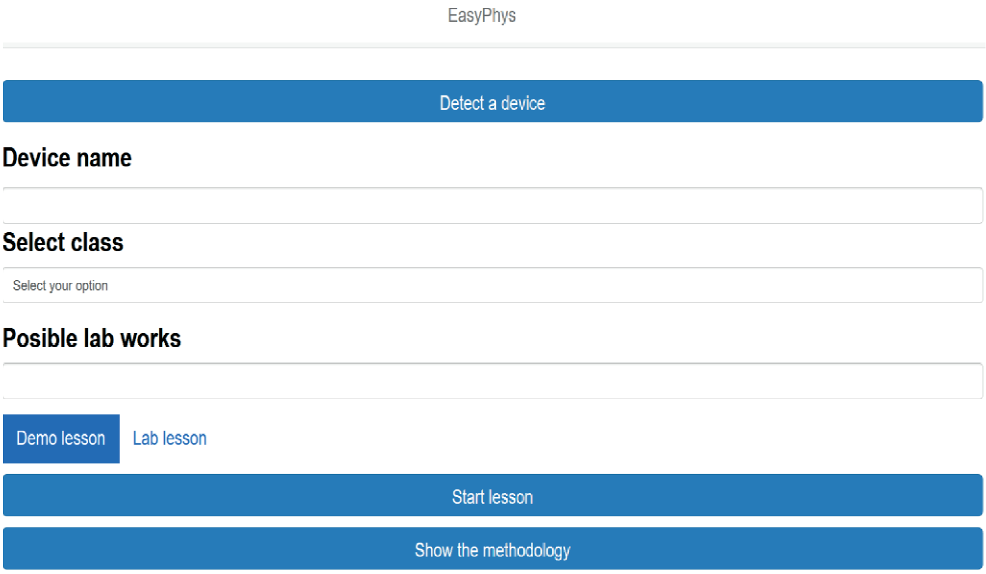


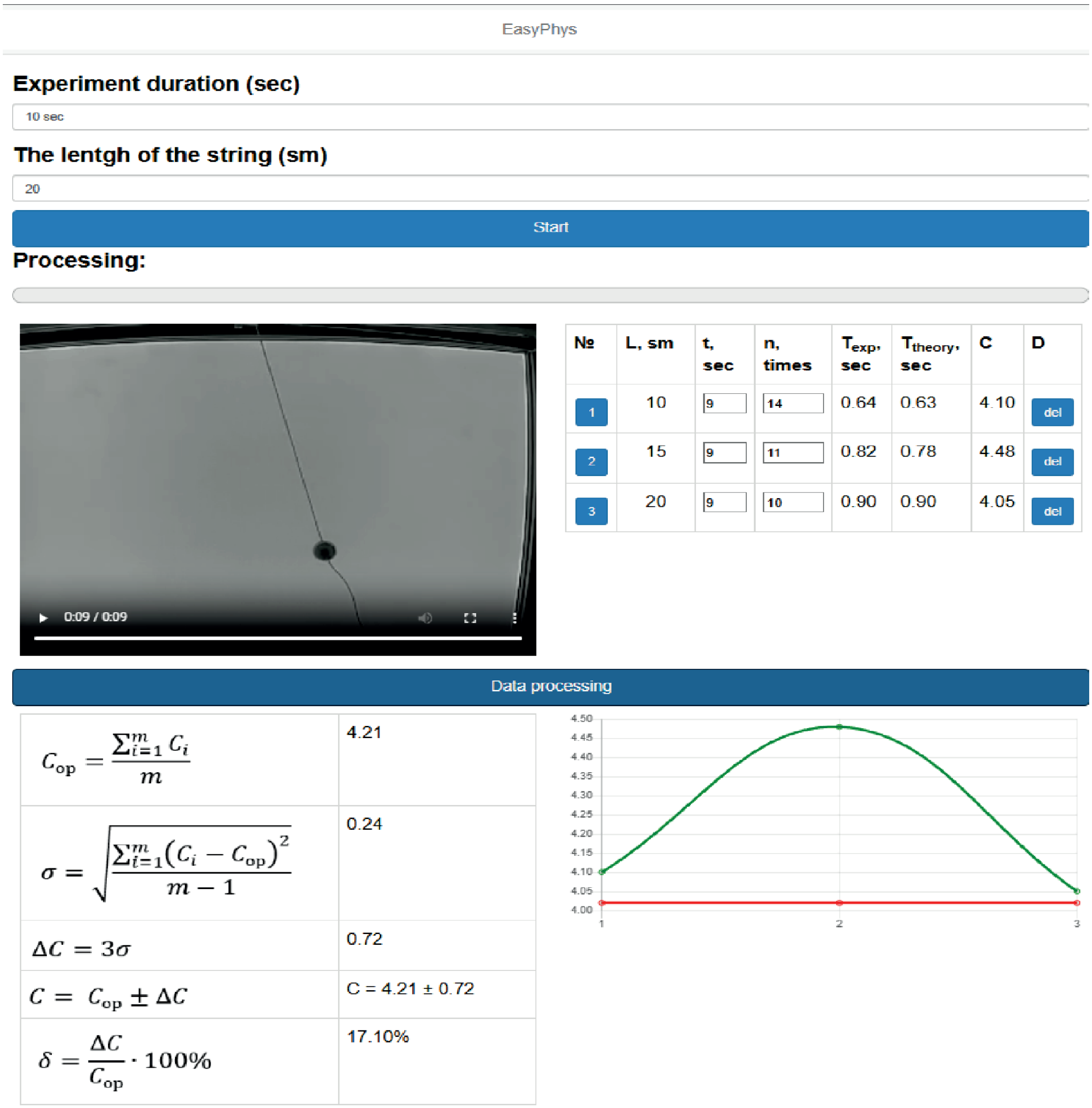
Figure 1. The main page

The main page does the following:

1. Identification of the connected laboratory module using a unique code;
2. Based on which laboratory module is connected, the user can select a class, topic and view the methodological manual;
3. Next, the user selects the type of lesson: demonstration or laboratory.

The laboratory lesson interface consists of the following items (Figure 2):

1. Field for selecting the duration of the experiment;
2. Field for entering initial data (for example, the length of a mathematical pendulum);
3. Button to start recording the experiment;
4. Progress scale to display the degree of completion of the task;
5. Video player for reproducing both the experiment itself and its results;
6. Table for experimental calculations;
7. Button for processing information;
8. Table and graph to display the results of the experiment.



Experiment duration (sec)
10 sec

The lentgh of the string (sm)
20

№	L, sm	t, sec	n, times	T_{exp}, sec	T_{theory}, sec	C	D
1	10	9	14	0.64	0.63	4.10	del
2	15	9	11	0.82	0.78	4.48	del
3	20	9	10	0.90	0.90	4.05	del

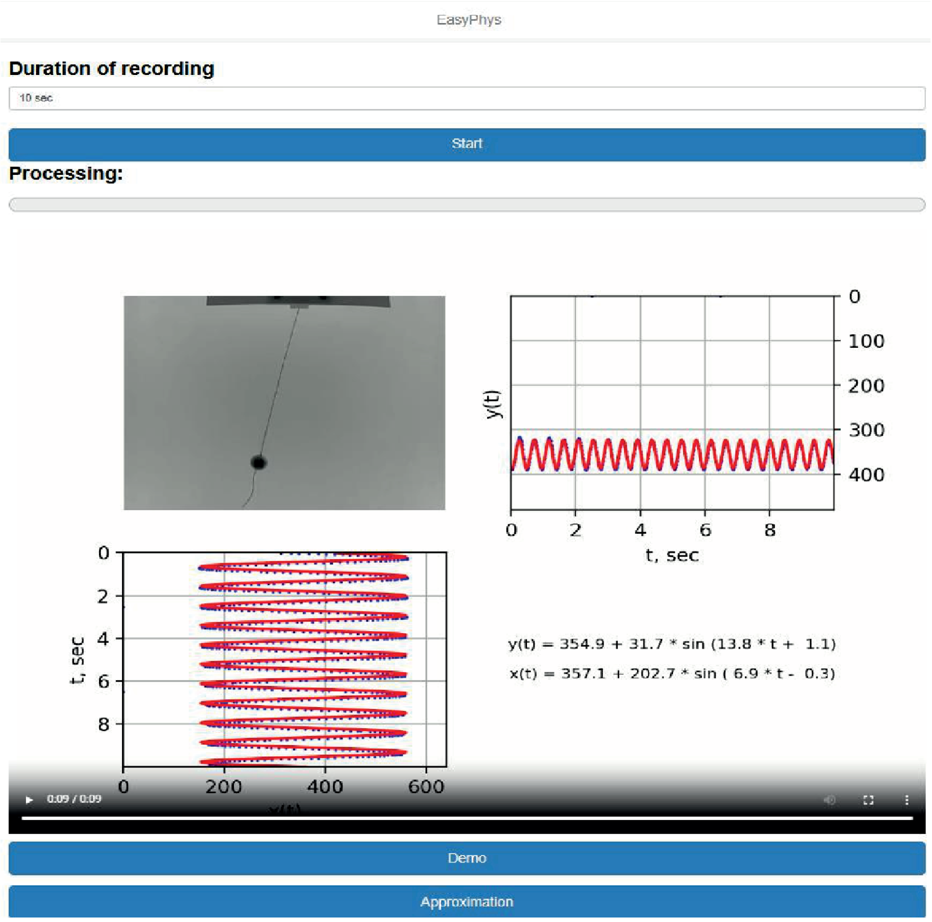
$C_{op} = \frac{\sum_{i=1}^{m} C_i}{m}$	4.21
$\sigma = \sqrt{\frac{\sum_{i=1}^{m}(C_i - C_{op})^2}{m-1}}$	0.24
$\Delta C = 3\sigma$	0.72
$C = C_{op} \pm \Delta C$	C = 4.21 ± 0.72
$\delta = \frac{\Delta C}{C_{op}} \cdot 100\%$	17.10%

Figure 2. Mathematical pendulum calculations Graphical user interface

The interface of the demonstration lesson consists of the following points (Figure 3):
1. Field for selecting the duration of the experiment;
2. Button to start recording the experiment;
3. Progress scale to display the degree of completion of the task;
4. Video player to reproduce the experiment and its results;
5. Button for performing processing necessary when demonstrating the experiment;
6. Button for performing processing necessary when approximating the obtained results.

Let us first consider the existing standard method for tracking the movement of a mathematical pendulum. A simple pendulum is created by hanging a weight on a string. Students need to calculate the period of oscillation. This is done by averaging the time spent on n swings. Students use a stopwatch to measure time and a pointer as a reference. The experiment can be repeated if necessary with a thread of different lengths [26].

The purpose of this experiment is to use the resulting period to calculate gravitational acceleration (g). This classic full-scale method has several disadvantages, such as low accuracy, spending significant time on experiment and measurements, the presence of air resistance creating damped oscillations, inaccuracy in understanding the influence of different amplitudes on the period, the characteristics of the movement of the pendulum are not illustrated and the impossibility of measuring its speed in several points in one cycle.



Duration of recording: 10 sec

y(t) = 354.9 + 31.7 * sin (13.8 * t + 1.1)

x(t) = 357.1 + 202.7 * sin (6.9 * t - 0.3)

Figure 3. The demo lesson interface

It is now pertinent to consider now how this experiment can be upgraded with the help of a modular experimental installation (MEI) the “Mathematical Pendulum” oscillation has been developed for study, presented in Figure 4. The operating principle of the laboratory installation is based on the use of computer vision technology, i.e. systems for monitoring the ongoing physical process. The tracking system consists of a Raspberry Pi camera module, an image pre-processing subsystem, an object identification subsystem, and a data export subsystem.

MEI “Mathematical Pendulum”, which is a structure in the form of a stage (box), inside which a mathematical pendulum is placed, that is, a load suspended on a thread, and additionally attached to the structure are cameras and a minicomputer (Figure 4). All components of the installation are interconnected and also connected to a laptop or personal computer controlled by the teacher or student.

In this installation, a metal ball with a diameter attached to a thread is used as a load, the length of which, i.e. the pendulum can be changed. The pendulum (ball) is manually deflected from the equilibrium position, and it begins its oscillatory motion. The entire process of movement (oscillation) of the pendulum is recorded using a digital camera. After recording the movement of a mathematical pendulum, the video image is transmitted to a microcomputer and processed, and then the received information is transferred to a PC, and then all the characteristics of the oscillation are displayed on its screen.

Figure 4. MEI "Mathematical Pendulum"

Let's consider a practical lesson on checking the correctness of the Thompson formula. According to the Thompson formula (1), the period of oscillation of a mathematical pendulum is defined as depending on the length of the pendulum

$$T = 2\pi\sqrt{l / g}, \quad (1)$$

where L is the length of the thread, g is the acceleration of gravity. During the experiment, it is necessary to change the length of the thread several times (at least 7 times) and measure the period of oscillation of the pendulum. To carry out the measurements, do you need a stopwatch to measure the time? Necessary for a complete n-fold oscillation of the thread and a millimetre measuring tape to measure the length of the thread. As a result, the period of oscillation of the pendulum is determined by the formula (2):

$$T = t / n \ , \quad (2)$$

where t is the time measured with a stopwatch, n is the number of complete oscillations performed by the pendulum during this time. We transform equation (1) into the form

$$T^2 / L = 4\pi^2 / g = C \quad (3)$$

as can be seen from formula (3), if Thompson's formula is correct, then the ratio of the square of the pendulum period to the length of the thread will have a constant value and its numerical value should be equal to 4.02 in approximation. It is hereby denoted the constant value determined in accordance with equation (3) by the letter C. Then the results of the experimental measurements should be filled in the following table 1.

Table 1. Results of experimental measurements

№	L, cm	t, s	n	T, s	C
1	15	7.81	10	0.781	4.07
2	18	8.68	10	0.868	4.19
3	27	10.43	10	0.104	0.04
m	20	8.97	10	0.58	2.77

This m, shown in the table 1, is the number of experiments conducted according to different thread lengths. Next, it is necessary to process the results of experimental measurements to check the correctness of the Thompson formula. So, in order to process the results of the experiment, first of all, the average value of the quantity is determined, which is designated as C (4):

$$C = \sum_{i=1} C_i / m \tag{4}$$

Now we calculate the standard deviation of the value C using the following formula (5):

$$\sigma = \sqrt{(\sum_{i=1}^{m} (c_i - c_{av})^2) / (m-1)} \tag{5}$$

According to the "three sigma rule", the absolute error (6) arising when measuring the value of C from experiment is equal to:

$$\Delta C = 3\sigma \tag{6}$$

If this is so, then the value of the quantity C, determined by experiment, must be presented in the form (7):

$$C = C_{AV} \pm \Delta C \tag{7}$$

As the final result of processing the results of experimental measurements, i.e. to determine the correctness of the Thompson Formula, it (8) is necessary to calculate the relative error of the determined value:

$$\sigma = (\Delta C / C_{av}) \cdot 100\% \tag{8}$$

If the relative error does not exceed 7%, we conclude that Thompson's formula is indeed correct and that it is otherwise incorrect. Using the formulas above, the student can independently perform calculations and fulfil the objective of the practical work. Moreover, we can perform these calculations automatically through our laboratory set-up. As a result, it can be verified that automatic calculations provide greater accuracy than manual ones. To do this, it is enough to automatically determine the oscillation period in each experiment performed.

For pendulums of different lengths (15 cm, 18 cm, 20 cm, 21 cm, 22 cm, 25 cm, 27 cm), we determined its oscillation periods in three different ways:

- Measurement of the theoretical value using Thompson's formula;
- Manual measurement using a stopwatch;
- Measurement using computer vision technology.

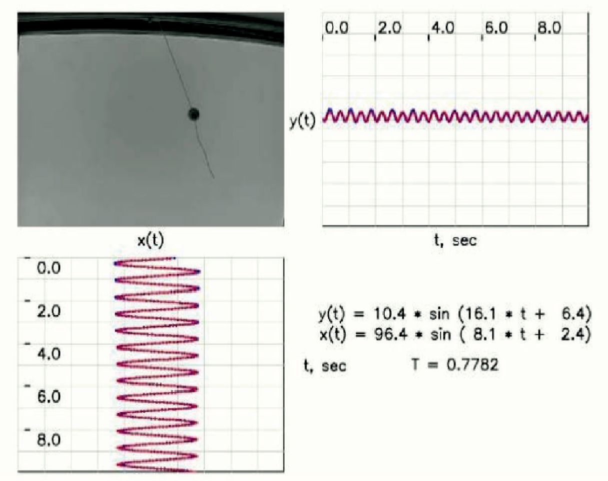
Consideration is given to the algorithm for determining the oscillation period of a mathematical pendulum using computer vision technology. The video is recorded via Raspberry Pi cameras with 90 FPS, 640x480 resolution, in MP4 format with the AVC1 codec, using the OpenCV library. The video is then saved in the media directory on the server. When the Demo button is pressed on the user graphical interface developed specifically for our device, the saved video is processed frame by frame to determine circles in the video data. Figure 2 shows the appearance of this user graphical interface.

Each frame is read using the Open CV library to determine the coordinates of the pendulum weight (represented as a circle in the video). The frame is converted to large-scale using the cvtColor function. This is necessary to simplify the analysis of the image, since the circle detection algorithm only works with large-scale images. Then the median Blur function is used to reduce noise in the image by median blurring.

Circles are detected using the Hough method, using the Hough Circles function of the Open CV library. The result is the coordinates of the centres and the radii of the found circles (if any). The processed video is saved in MP4 format with the AVC1 codec and a resolution of

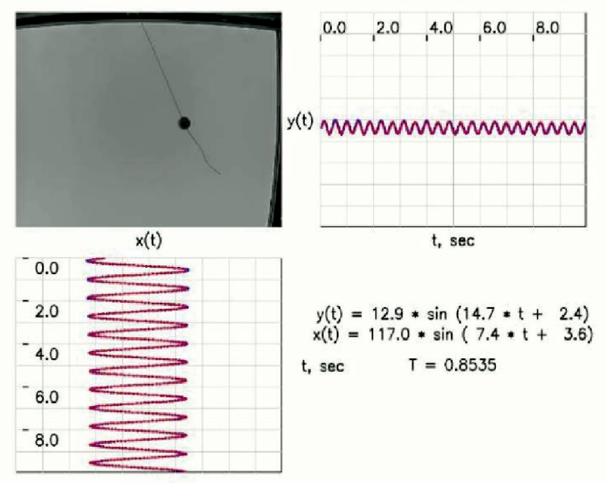
1280x960. The video file is created from three sub graphs: a video frame with the definition of the circle coordinates, a graph of the $y(t)$ dependence, and a graph of the $x(t)$ dependence on time.

When the Approximation button is pressed, the saved video is processed frame by frame to approximate the dependence of $y(t)$ and $x(t)$ on time. This is necessary to determine the parameters of the pendulum oscillations. The shape of the pendulum oscillations follows a sinusoidal shape, so the curve_fit() function from the Open CV library is used to approximate the y(t) and x(t) dependences. The curve_fit() function finds the optimal parameters for approximating the data to a sinusoid using the least squares method. The processed video is saved in MP4 format with AVC1 codec and 1280x960 resolution. The video file is created from three sub graphs: the last frame from the video, the graph of the y(t) and x(t) dependence with approximation, and text with the parameters of the sinusoidal dependences y(t) and x(t). Figures 5-11 show the results of measuring the oscillation period of a mathematical pendulum using computer vision. These figures show the appearance of the approximation function describing the oscillatory motion of the pendulum and the values of the oscillation period found using these functions.



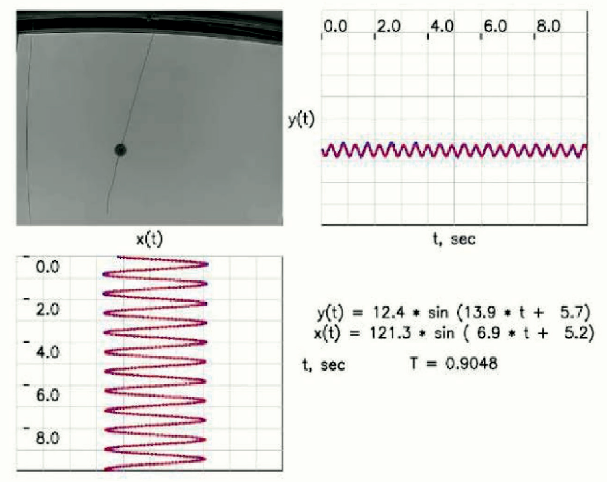
```
y(t) = 10.4 * sin (16.1 * t +  6.4)
x(t) = 96.4 * sin ( 8.1 * t +  2.4)
T = 0.7782
```

Figure 5. Measuring the period of oscillation using computer vision for a pendulum length of 15 cm. The period is 0.778 s.



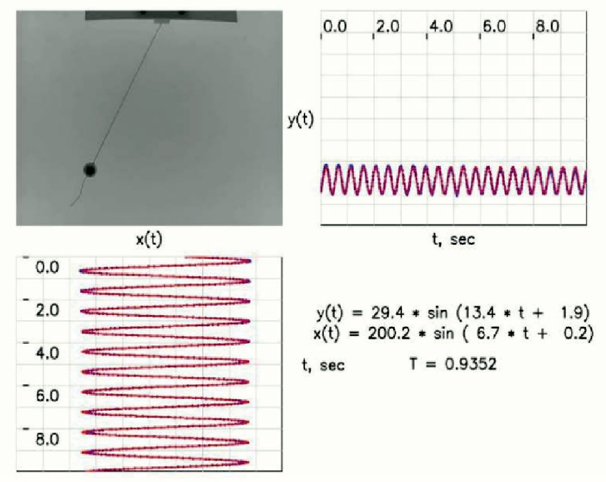
```
y(t) = 12.9 * sin (14.7 * t +  2.4)
x(t) = 117.0 * sin ( 7.4 * t +  3.6)
T = 0.8535
```

Figure 6. Measuring the period of oscillation using computer vision for a pendulum length of 18 cm. The period is 0.853 s.



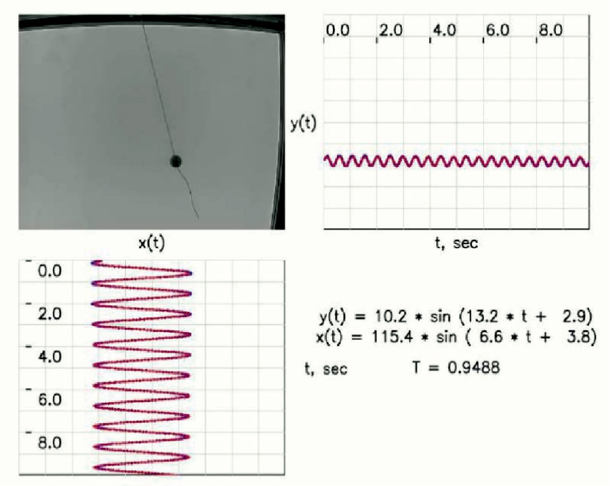
```
y(t) = 12.4 * sin (13.9 * t +  5.7)
x(t) = 121.3 * sin ( 6.9 * t +  5.2)
T = 0.9048
```

Figure 7. Measuring the period of oscillation using computer vision for a pendulum length of 20 cm. The period is 0.905 s.



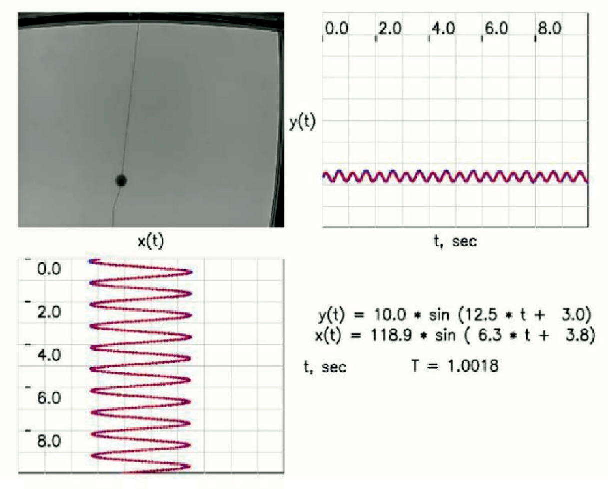
```
y(t) = 29.4 * sin (13.4 * t +  1.9)
x(t) = 200.2 * sin ( 6.7 * t +  0.2)
T = 0.9352
```

Figure 8. Measuring the period of oscillation using computer vision with a pendulum length of 21 cm. The period is 0.935 s.



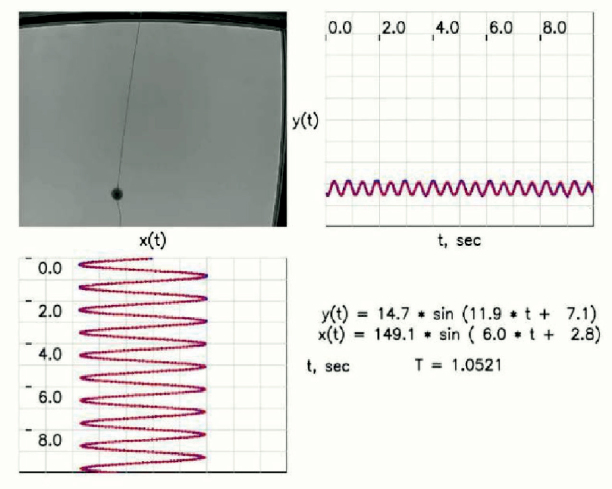
```
y(t) = 10.2 * sin (13.2 * t +  2.9)
x(t) = 115.4 * sin ( 6.6 * t +  3.8)
t, sec         T = 0.9488
```

Figure 9. Measuring the period of oscillation using computer vision for a pendulum length of 22 cm. The period is 0.949 s.



```
y(t) = 10.0 * sin (12.5 * t +  3.0)
x(t) = 118.9 * sin ( 6.3 * t +  3.8)
t, sec         T = 1.0018
```

Figure 10. Measuring the period of oscillation using computer vision for a pendulum length of 25 cm. The period is 1.002 s.



```
y(t) = 14.7 * sin (11.9 * t +  7.1)
x(t) = 149.1 * sin ( 6.0 * t +  2.8)
t, sec         T = 1.0521
```

Figure 11. Measuring the oscillation period using computer vision for a pendulum length of 27 cm. The period is 1.052 s.

And the third method was when the oscillation periods of the pendulum were measured manually. During the experiment, the time spent by the mathematical pendulum on completing 10 full oscillations was measured. The time was determined by a mobile phone stopwatch, the accuracy of which is 1/100 of a second.

Thus, all the values of the oscillation periods of the pendulum were obtained, found in three different ways. The values of these periods are given in the table 2. The table 2 also shows the deviations of the measured values of the periods from the theoretical values.

Table 2. Values of the oscillation periods of the mathematical pendulum for different lengths, found in three different ways

Thread length	**T, computer vision**	**T, experimenter**	**T, theory**	**Computer vision deviation**	**Manual deviation**
15 см	0.778	7.81/10=0.781	0.777	0.13%	0.51%
18 см	0.853	8.68/10=0.868	0.851	0.23%	2%
20 см	0.904	9.04/10=0.904	0.897	0.78%	0.78%
21 см	0.935	9.29/10=0.929	0.919	1.74%	1.09%
22 см	0.949	9.53/10=0.953	0.941	0.85%	1.27%
25 см	1.002	10.07/10=1.007	1.003	0.1%	0.4%
27 см	1.052	10.43/10=1.043	1.042	0.96%	0.1%
Average deviation value:				0,68%	0,86%

The implementation, study and comparison of three measurement methods and the identification of deviations presented in the table 2 demonstrate that in 4 out of 7 cases the measurement method based on computer vision determines the oscillation period of the mathematical pendulum more accurately, i.e. gives a value closer to the theoretical one. Manual measurement was more accurate than computer vision only in two out of seven cases. This means that we can conclude that computer vision is capable of measuring the oscillation period of the pendulum more accurately than a person. In addition, the relative accuracy of determining the coefficient C was calculated using formula 8 (according to formula 3). The relative accuracy of calculating this coefficient using computer vision technology was 3.66%, and using the manual method – 3.82%. Thus, we are once again convinced that computer vision, although a little, still measures the oscillation period of the mathematical pendulum more accurately, i.e. makes measurements more accurately.

At this stage the topic is addressed how to use the developed MEI "Mathematical Pendulum" when explaining the topic "Oscillatory Motion" (9th grade) without connecting it to a computer to form the concept of oscillatory motion, understand the conditions for the occurrence of oscillatory motion and form knowledge of the basic quantities characterizing oscillatory motion.

1. The suspended body in the installation (MEI) is an example of a body that can perform a periodic oscillatory motion in time, i.e. oscillation, if it is taken out of the equilibrium position.
2. If the pendulum is taken out of the state of rest, then oscillatory motion without the influence of external forces, i.e. free oscillation, will be demonstrated.
3. This system itself is an example of an oscillatory system.
4. The stable state of this oscillatory system, i.e. the presence of the thread in a vertical position is the equilibrium position.
5. By moving the ball (load) on the thread to the maximum distance from the position (point) of equilibrium, the concept of oscillation amplitude is introduced.
6. By determining the time it takes for one complete oscillation to complete, the physical quantity characterizing the oscillatory motion as a period is demonstrated and its value is determined.
7. By determining the number of movements or oscillations performed by the system per unit of time, the concept of oscillation frequency is introduced and its value is determined. Now, for the visual introduction of other physical quantities considered in this section, such as harmonic oscillation, geometric model of harmonic oscillation, cyclic frequency and oscillation phase, it is recommended connecting this MEI to a PC to display the physical process occurring in it on a large screen.

8. As soon as the video camera of the installation is connected, it will determine what kind of installation it is by reading the unique code of the MEI (in our case, it will recognize it as the MEI “Mathematical Pendulum”.

9. Next, the teacher or lecturer will select the required class (9-11 grades) and the corresponding laboratory work.

10. Then the teacher or lecturer manually takes the mathematical pendulum out of the equilibrium position, after which the pendulum begins to oscillate, which will be visible to all observers.

11. At the same time, the process of pendulum oscillation will be displayed on the computer (laptop) screen or on the demonstration screen, identical to the process performed in the IEC, i.e. a real system in real time (Figures 5-11).

12. Also, a graphic representation of the oscillatory motion will be displayed on the screen for the students to see, which is a confirmation of the harmonic oscillation, i.e. the oscillation according to the law of sine or cosine. This is how the concept of harmonic oscillation is introduced (Figures 5-11).

13. Then students should fill out the table with the data obtained during their manual experiment.

14. As soon as this table is filled in by students, a table will appear with all the results of the experiment, automatically calculated by the computer, such quantities characterizing the oscillation as period T, amplitude A, oscillation frequency ν, cyclic frequency ω and oscillation phase.

15. Here, too, to perceive and understand the essence of harmonic oscillation, you should use the “stop” and “slow process” buttons located under the video of the oscillatory system. For example, by clicking on the “stop” button, you can stop the oscillation process to record and determine all its parameters at a given time and see their values in the table and on the graph too, they will be highlighted in it. By clicking on the “slow process”, students will see the entire oscillatory process and the vibration parameters corresponding to each coordinate (displacement point) in the table.

16. Moreover, it is possible to change the length of the thread in the actual MEI. A video camera and a minicomputer (or thanks to computer vision) will immediately determine its length and information about this oscillation corresponding to these changes will appear on the screen.

17. Based on the analysis of what they saw and received about the oscillatory motion, students gain knowledge in the chapter “Oscillations and Waves” and prepare to perform the laboratory work “Determination of the acceleration of free fall using a mathematical pendulum.”

Using the MEI “Mathematical Pendulum”, you can explain the material in the paragraph “Transformation of energy during oscillations. Equation of oscillatory motion”, on topics such as “The law of conservation of energy for a mathematical pendulum. Maximum speed of an oscillating body”, “Coordinate of an oscillating body”, “Equation of oscillatory motion”, also the paragraph “Oscillation of a mathematical pendulum” on the topics “Conditions under which harmonic oscillations occur”, “Period and natural frequency of oscillations of a mathematical pendulum”. In addition, many topics in the chapter “Mechanical Vibrations” of grade 11, such as “Equations and graphs of harmonic vibrations”, “Conditions for the occurrence of free harmonic vibrations”, “Laws of harmonic vibrations”, “Phase of vibrations. Relationship between the phase of harmonic oscillations and the period”, “Equations of harmonic oscillations”, “Speed and acceleration during oscillatory motion”, “Graphs of harmonic oscillations. “Phase shift” can also be clearly demonstrated on the basis of the MEI “Mathematical Pendulum”, which will allow you to carry out many experiments in situ, simultaneously visualize them on the demonstration screen and make instant calculations of the parameters of the oscillatory process.

Thus, during the study

- physical processes in mechanics have been identified that need to be demonstrated in reality in educational laboratories;
- organized and wrote technical specifications for the development of a digital experimental installation “Mathematical Pendulum”;
- libraries of system modules have been developed for processing experimental data in the process of applying computer vision technology;
- models of key elements of the software and hardware complex “Mathematical Pendulum” were designed and created;
- software interface windows-applications were created to control the experiment process;
- complete methodological support has been developed for the use of the laboratory complex “Mathematical Pendulum” in the educational process in order to demonstrate full-scale mechanical processes;
- a prototype of the laboratory installation “Mathematical Pendulum” was developed.

Discussion

Thus, based on the results of the study and testing of the developed laboratory installation at Seifullin University, it is posited that it possesses number of advantages;

- is an inexpensive solution that does not require additional equipment; a powerful tool for solving problems related to providing research and distance education.
- increases and maintains the attention and motivation of students, their ability to self-learn; provides a new laboratory experience to complement the existing physics laboratory; improves learners’ skills, understanding, problem-solving and creativity; supports simultaneous student connections.
- enriches the teaching process, making practical classes more attractive for students; represents a special approach to conducting an experiment; allows for learning outcomes comparable to traditional laboratories; provides observation and study of the characteristics of physical phenomena, processes and patterns, the recording of which is difficult or impossible in an ordinary real experiment, as well as the study of dynamically occurring phenomena or processes; provides a graphic interpretation of phenomena or processes to reveal their essence.

The results of the study on the development of modern laboratory installations in physics based on computer vision and an effective educational manual for it, as well as their experimental testing, confirmed their operability and effectiveness when used in the educational process. Thanks to the use of computer vision technology, the developed laboratory installations made it possible to track the movement of bodies and physical processes, improve the quality and speed of measurements, broadcast and save videos of demonstration and laboratory experiments. The obtained research results are consistent with existing concepts of modern organization of the educational process and offer a comprehensive solution for conducting laboratory experiments and demonstrating physical processes in full-time and distance learning formats. The study and its results have theoretical and practical significance in teaching physics in schools and universities. In the process of creation are other modular experimental installations in mechanics, such as “Inclined Plane”, “Oberbeck Pendulum”, “Physical Pendulum”, “Body thrown at an angle to the horizon”, “Stokes” and others.

Conclusion

Thus, the development of laboratory complexes based on computer vision technology and their testing in the educational process allows us to draw the main conclusion that the use of the modular experimental set-ups we have developed in teaching physics is a new teaching model with a great future in schools and universities around the world, and the set-ups are offline and online learning tools that bring a new dimension to learning and science, thanks to using computer vision technology, opening up new learning opportunities and perspectives that cannot be fully explored in a traditional physics laboratory. Testing of laboratory work using computer vision technology on the laboratory set-ups we developed confirmed that this method provides more accurate and theoretically close values of the calculated parameters, and also allows students to independently conduct the entire experiment and self-check the obtained calculation results. But at the same time, the developed laboratory modular installations make it possible to conduct only those experiments where the physical processes themselves are visualized in space and time. Additional developments are required to expand the capabilities of the installations. In the future, laboratory facilities in other areas of physics are planned to be developed.

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