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DEVISING AN APPROACH TO CONDUCTING FULL-SCALE EXPERIMENTS IN PHYSICS THAT PROVIDES FOR THE IMPROVED EFFICIENCY WHEN MEASURING PHYSICAL QUANTITIES

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The object of this study is a procedure for measuring physical quantities under laboratory conditions at educational institutions. The issue related to this case is the lack of any comprehensive method and technical solution suitable for the experimental study of physics in both offline and online learning formats. To solve this problem, an approach has been proposed, based on computer vision technology and training special neural models to recognize objects in video frames that perform mechanical movement.

The idea of the proposed approach is based on the hypothesis that by measuring the position of an object in video frames with sufficient accuracy, it is possible to determine the functional type of the law of its motion. Further, knowing the function of the law of motion, it is possible to calculate any physical quantities describing the process under consideration. The idea is implemented in the form of a technical solution, which is a set of prototypes of automated laboratory devices.

The choice of the method for determining the law of motion was carried out using the analysis of the recognition error, measurement error, speed and resistance to external conditions of the Hough algorithmic method and the YOLOv8n neural network model. It is shown that the neural network method YOLOv8n has very high accuracy but low performance. The Hough method shows high performance but lower accuracy and resistance to external conditions. It was found that the accuracy of the YOLOv8n method is 4 times higher, but the execution speed is 10 times lower than that of the Hough method. However, in the case of artificial lighting and fixing the distance from the camera to objects, the Hough method provides 99.9% accuracy in recognizing an object in video frames.

The obtained prototypes of devices can be used for further research to determine their impact on the quality of physics education

Keywords: video processing, laboratory setups, YOLOv8n, Hough method, computer vision, online learning

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1. Introduction

The Covid-2019 pandemic has sharply exposed the problem of the lack of online educational resources and technologies capable of providing the necessary quality of teaching natural science disciplines. In addition, there are regions in the world where classes in schools are often cancelled due to deteriorating weather conditions. For example, such a practice is often used in Astana, the capital of the Republic of Kazakhstan, in winter. Thus, a large number of students regularly lose the opportunity to attend educational institutions for a long time.

The strict need to conduct classes within the walls of educational institutions is acutely felt when teaching physics, since physics is a quantitative science, where natural experiments are an important component. All these experiments are carried out on different equipment and with the help of various devices whose modern implementations are completely unsuitable for use in online classes.

In this regard, there is a need to search for and implement new methods for designing devices that would allow natural experiments in physics and could provide the following capabilities:

– ensuring high accuracy of measuring physical quantities;

– ensuring reasonable performance for organizing experiments in real time;

– providing mechanisms for visualization and broadcasting the process of conducting a natural physical experiment via the Internet.

Thus, the relevance of our research topic relates to its direct application in the educational process, where a natural laboratory experiment is important for improving the quality of knowledge. The conventional system of conducting laboratory classes and laboratory equipment, although widely used, suffers from significant limitations. The process of conducting an experiment requires constant manual monitoring and processing of the physical process being studied. All this makes the process of conducting educational experiments labor-intensive, time-consuming, and subject to human errors and routine actions, which reduces its overall effectiveness.

Therefore, research into methods for providing online physics classes related to the demonstration of mechanical phenomena in natural experiments remains critically important.

2. Literature review and problem statement

Paper [1] reports a simple mechanism for tracking objects or processes based on computer vision in order to improve the quality of measurements and new ways of conducting experiments. The authors prove that the use of computer vision can solve many problems and perform several additional functions, such as tracking several objects simultaneously over a long period of time. In the method they propose, a digital camera was used to record video with subsequent pre-processing. Image processing was carried out using an average personal computer and MATLAB software. The method they propose estimates the location of an object many times in one cycle, which allows one to clearly determine the behavior of simple harmonic motion, the relationship between speed, acceleration, and displacement. This method is more efficient, accurate, and provides deeper knowledge for the student, the researchers believe. The main disadvantages of the proposed method of conducting an experiment include the lack of integration of its hardware and software elements into a single system. There are also such disadvantages as the lack of the ability to broadcast the process over the Internet in real time, suitability only for a special case (a mathematical pendulum).

Work [2] reports the results of a study in which computer vision is used to examine the dynamics of an object's motion (a mathematical pendulum) in order to automatically and contactlessly determine its frequency. A mobile phone camera is used to record the oscillatory process on video. The results of the experiment using computer vision are confirmed by theoretical calculations and have an accuracy of 99%. The experimental values of the corresponding natural frequencies for different pendulum lengths are quite close to the values determined by the computer vision method. The main disadvantage of this approach is the use of a mobile phone to record the process, which is not the most effective tool since it requires additional actions and tools for processing and analyzing the recorded video image. All these additional actions are performed separately, which makes this approach unsuitable for organizing online learning.

In [3], the authors propose a revolutionary method that allows real-time measurement of the distance between the camera and the object using computer vision. Owing to the algorithm they developed, built into the smart camera, it is possible to perform two-dimensional measurements of the distance between the point of the camera lens and the object, i.e., determine a fairly accurate distance, even if the object has complex three-dimensional shapes. When an object moves in space, the camera can perform accurate and fast measurements in real time to determine its speed. This method is based on image processing using the Python programming language, a powerful OpenCV library running on the Raspberry Pi board. This approach is much more efficient compared to measuring the distance manually using a measuring device. At the same time, this method makes it possible only to determine the distance between the camera and the object and does not make it possible to calculate such important kinematic characteristics as instantaneous speeds and accelerations.

Paper [4] presents a computer vision-based system that can detect, track, and measure the distance traveled and the time spent by an object during free fall. The system is implemented using OpenCV libraries. The result of analysis of the freely falling object is provided to the students through a web page. The entire process of recording the distance and time spent by the object is automated using computer vision. Object detection algorithms are used to identify a moving object in the video. In the conventional conduct of this experiment, measuring the time for a freely falling object is a tedious process because the object has a high speed and the time it takes for the object to fall is measured in milliseconds. Manually recording the time can lead to large errors in determining physical quantities, such as the acceleration of gravity. The setup designed by the researchers consists of a webcam and a computer. The experimental results were quite accurate when compared with the results obtained from the fundamental equations of motion. The program runs on any single-board computers such as Raspberry Pi, Beaglebone Black to create an autonomous system for this experiment. However, the device has several drawbacks, for example, the experimental results are highly dependent on lighting and a certain distance between the object and the camera and may be inconsistent.

The authors of [5] developed a data collection and analysis system for physical education, consisting of a laptop, a webcam, and software. A laptop webcam with a high resolution and a frame rate of more than 30 frames per second and 640×480 pixels, respectively, is used to record the movement of objects, which is sufficient to analyze the nature of the movement of a moving object in standard dynamic experiments. The software is implemented on Windows 7 using the VisualStudio2010 programming environment developed by Microsoft USA. The Qt visual programming environment is used to implement the graphical user interface. The function of identifying moving objects is implemented using OpenCV. Performing an experimental measurement of instantaneous values of kinematic quantities with this setup yields an error of about 17%, which is quite large for high-precision experiments. In addition, this system is not intended for organizing online classes.

In [6], the authors describe a simple and inexpensive method for studying pendulum motion and head-on elastic collisions, following the Bring-Your-Own-Device philosophy. A popular inexpensive toy, Newton's cradle, is used to create a pendulum or collision system, and the motions of its spheres are tracked using a smartphone using video analysis. The recording is done using the free Open Camera app, which allows the user to easily control fps. A second app (VidAnalysis Free) is used to track the position of each of the spheres. The video sequence is loaded from the gallery into the video analysis tool. The app first requires setting up the axis system and length scale before tracking the positions of each sphere by tapping the screen frame by frame, creating position-versus-time graphs. After processing all the frames, the app displays several graphs and allows easy export of the data to a csv file. In this approach to measuring physical quantities, the use of a smartphone limits the tracking process and requires additional steps and video analysis tools. All these additional processing methods make this method unsuitable for use in online learning.

In work [7], scientists use an inexpensive single-board computing device Raspberry Pi to perform laboratory work in physics. The Python software package together with the Raspberry Pi manages the acquisition, display, and storage of data. The authors believe that digitization of didactic experiments is possible and useful. The use of devices such as Raspberry Pi is inexpensive and helps conduct relevant experiments for the learning process, in this case, experiments to study Ohm's law and the Peltier effect. In addition, by displaying it on a large screen (for example, on a smart board), it is possible to make digital experiments visible to the entire class, which is not always possible in the case of classical experiments. The authors conclude that simple physics experiments should be supplemented by digitization of didactic experiments in order to achieve strong motivational effectiveness and, therefore, to achieve strong development of learning skills and creativity. The missing element in this system is the manual measurement and processing of data obtained during the experiment.

Another electronic device for use in physics experiment is Arduino microcontrollers, which are affordable compared to other experimental kits for teaching science, technology, engineering, and mathematics (STEM). In [8], two different physics experiments were conducted using an easy-to-design experimental setup using Arduino, a force sensor, and a metal sphere attached to a rope. Educational activities of this type can both create maximum benefits for students in STEM fields during limited periods of study and contribute to equality of opportunity in education due to its economic nature. However, the use of Arduino-type microcontrollers imposes serious limitations on the functionality of the devices, such as broadcasting the process over the Internet, and connecting resource-intensive computing algorithms related to image processing, artificial neural networks, etc.

Study [9] reports a computer vision system for obtaining data on the position of the body, where human observations have conventionally been used. A simple algorithm based on color discrimination automatically determines the location of the object of interest. Experiments are monitored in real time using inexpensive cameras. The authors provide examples to illustrate the applicability of the system they created for autonomous data acquisition. This system uses only one of the many capabilities of computer vision, such as color discrimination, in order to simultaneously track the movement of several objects. However, this solution does not provide for measuring the instantaneous values of the kinematic characteristics of the movement of the tracked objects and does not implement the possibility of using it in online lessons.

In work [10], researchers also use conventional video cameras to record and analyze the vibration of visible objects. Through spatial and temporal analysis, subtle changes in the video recording of an object (a simple harmonic pendulum) vibrating at a low frequency are recorded. The information obtained allows them to predict the physical properties of the object and the force under which the movement occurs. The developed algorithm is used to process the video and extract the pendulum weight motion using visual vibration analysis. The cameras act as a simple vibration sensor with a higher spatial resolution than the vibration measuring devices used in other works. Thus, the authors propose a new way to use the camera as a powerful tool for vibration analysis. However, the proposed method analyzes only vibrations and does not consider other types of mechanical motions and does not solve the problem of organizing online learning in physics.

There are many studies on the implementation of experiments in a virtual environment. Their authors believe that when studying physics, an experiment is a source of discovery and problem exploration by students, which plays a crucial role in physics and is also the focus of teaching physics. In paper [11], they illustrate the role of a physics learning platform based on a virtual experimental scene, based on the advantages of virtual technology. The results of the study showed that the platform they designed could help students better understand the work of physics experiments. But the authors are more inclined to the virtual format of the experiment, rather than the natural one.

Despite some effectiveness, the considered approaches to conducting experiments and the corresponding laboratory setups demonstrate the following limitations and disadvantages:

– lack of integration of hardware and software elements into a single system;

– ineffectiveness of using a mobile phone to record the process and the need for additional actions and tools for processing and analyzing the video image recorded by it;

– dependence on additional conditions, such as lighting and a certain distance between the object and the camera;

– unacceptably large error in measuring instantaneous values of physical quantities;

– not using modern technologies for non-manual measurement and data processing;

– not using the full range of computer vision capabilities;

– lack of physical contact and visibility.

Thus, further research and development of approaches to measuring physical quantities in the processes of online physics classes are needed, including solving the task of integrating all components into a single system.

3. The aim and objectives of the study

The purpose of our research is to improve the efficiency of experimental measurement of physical quantities for educational purposes using computer vision and artificial neural networks. Achieving this goal will allow the design of experimental setups suitable for studying the laws of physics and using in online learning.

To achieve the goal, the following tasks are set:

– to devise a method for determining the functional type of the law of motion of objects in video frames using computer vision;

– to select the most suitable method for recognizing objects in video frames.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is the procedure for measuring physical quantities under laboratory conditions at educational institutions. The study is based on the hypothesis that by measuring the position of an object on video frames with sufficient accuracy, it is possible to determine a clear functional form of the law of its motion. Further, based on the function of the law of motion, it is possible to calculate any physical quantities characterizing the process under consideration.

It is assumed that it is possible to calculate quite accurately all other kinematic characteristics of motion, such as instantaneous velocity and acceleration by differentiating the law of motion of the body. However, direct digital differentiation of the law of motion of the body will not make it possible to obtain truly instantaneous values of velocity and acceleration. Firstly, in this case, these values can only be obtained at discrete moments in time. Secondly, they will have a large error. In order to obtain more accurate values of kinematic characteristics, it is necessary to know the functional form of the law of motion, which can only be established using data approximation methods or the Kalman filter.

In addition, it is assumed that not all methods of recognizing objects in video frames can be suitable for use when designing laboratory setups since they can have various limitations. Such limitations include increased requirements for computing resources, poor recognition accuracy, and dependence of accuracy on external conditions (lighting level, distance from camera to object, etc.).

4. 2. Experimental procedure

To experimentally verify the correctness of the hypotheses and assumptions put forward, prototypes of the following laboratory devices were designed:

– a mathematical pendulum;

– an inclined plane;

– a physical pendulum;

– motion of bodies in a viscous liquid.

Fig. 1–4 show the general view of these devices.

As is known, the basic characteristic of a mathematical pendulum is its length. The length of the pendulum in this device is set using a screw mechanism located in the upper part of the horizontal axis, which in turn can also be moved up and down. When studying the movement of the pendulum, the camera filming the process is turned on only for a specified time, for example, for 10 seconds. Thus, a limitation on the duration of the time for examining the pendulum's movement is achieved.

The tilt angle of the device is set using a screw mechanism, to which a thread is attached, tied to the plane (Fig. 2). There are two mechanical touch sensors on the plane, located at the upper and lower points of the plane. These sensors are needed to automatically turn on and off the camera, which films the process of body movement along the inclined plane. This is done in order to automatically determine the beginning and end of the physical process. Thus, the length of the video file will be limited, which will ultimately lead to a sharp reduction in the time of video data processing.

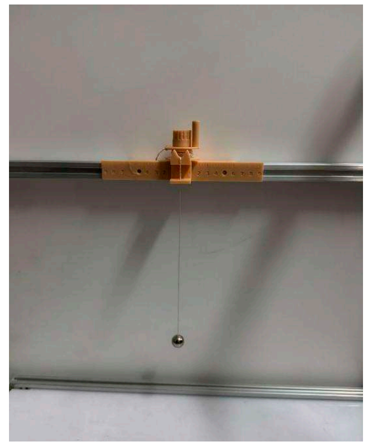

Fig. 1. General view of a laboratory setup for studying the law of motion of a mathematical pendulum

Fig. 2. General view of a laboratory setup for studying the law of motion of bodies on an inclined plane

Fig. 3. General view of a laboratory setup for studying the law of motion of a physical pendulum

The physical pendulum is a massive metal rod with many holes equally distributed along its length (Fig. 3). The holes are used to set the axis of rotation of the physical pendulum. The suspension point is made using a bearing in order to obtain a weakly damped oscillation. Here, as in the case of the mathematical pendulum, the duration of the process that is filmed on camera is set in advance, for example, 10 seconds.

Fig. 4. General view of a laboratory setup for studying the law of motion of bodies in a viscous liquid

This device consists of a transparent vessel filled with a viscous liquid, in this case glycerin (Fig. 4). With the help of this device, the law of motion of bodies under the action of gravity in a viscous medium is studied. The device can be used to study Stokes' law, determine the viscosity coefficient of a liquid, measure the resistance force of the medium, etc.

In all these devices, observation of the process, recording of the motion of bodies on a video camera, data processing, approximation of the functional form of the law of motion are performed according to a single algorithm and with the help of one universal device (measurement module). The general view of this measurement module from different angles is shown in Fig. 5.

Fig. 5. General view of the universal measurement module

The universal module consists of a single-board microcomputer Raspberry PI 5 model B, a special video camera for this microcomputer, and video data processing software. The choice of the Raspberry PI 5 model B microcomputer for the implementation of the data processing module is dictated by the fact that it is capable of operating in real time, has sufficient computing resources to support the functions of computer vision and artificial neural networks. Also, all Raspberry PI models have a network card, which allows them to be used to broadcast a computer screen during online lessons. In addition, all Raspberry PI models have input and output pins for connecting various sensors and peripheral devices to it.

To study the effect of lighting on the accuracy of video data processing, a special closed-type chamber was fabricated, where the lighting is set using a set of LEDs. In order to check the effect of lighting on the accuracy of measurements, experiments can be carried out both with and without artificial lighting. The general view and example of using this camera to study a mathematical pendulum are shown in Fig. 6.

Fig. 6. An example of using a special camera with artificial lighting to study the motion of a mathematical pendulum

Fig. 6 shows the moment when there is virtually no natural light in the room, and the pendulum oscillates against the background of a glowing screen. The oscillatory process is monitored using a measurement module. Peripheral devices are connected to the measurement module via the USB ports of the microcomputer: a monitor, keyboard, and mouse. One can also see that the current position of the pendulum is shown on the monitor. Accordingly, by demonstrating the monitor screen using programs such as Zoom, Microsoft Teams, etc., one can broadcast the process of conducting a real, natural experiment during online learning.

4. 3. Methods for detecting objects in video frames

Currently, there are many different algorithms and methods for recognizing objects in video frames. However, many of them require special conditions and large computing resources, which cannot always be implemented under the laboratory conditions at educational institutions. In this regard, in this paper, a simplification was adopted that for detecting objects in video frames, we can limit ourselves to considering the following two different methods that require the least computing resources:

– the algorithmic Hough method [12];
– the neural network method YOLOv8n (Nano) [13].

The task was to determine the most suitable method for recognizing objects in video frames for organizing online physics classes based on natural experiments to study the laws of mechanical motion. To assess the suitability of the considered methods for recognizing objects in video frames, the following indicators are introduced and used in this paper:

– object recognition error;
– measurement error;
– performance;
– resistance to external conditions.

An object may have different sizes and shades in different video frames during its movement. Accordingly, object recognition methods may make mistakes by not finding the required object in a specific video frame. In this case, the criterion for the object recognition error indicator is the ratio of the number of video frames where the object was not found to the total number of video frames.

It is assumed that even with correct object recognition in a video frame, its spatial coordinates within the video frame may be determined incorrectly. This, in turn, affects the accuracy of obtaining the law of object motion (the dependence of the object's coordinates on time), which will lead to an increase in the error in calculating various physical quantities obtained from this law of motion. The values of all these physical quantities calculated from the law of object motion are, in fact, indirectly measured values. As a rule, the measuring accuracy of any device is determined by its ability to give results close to the true value of the measured quantity.

If the indirectly measured quantity is not determined directly by a specific formula using directly measured quantities, then the measurement error of this quantity can be defined as the error of a random variable. In this case, to more clearly determine the measurement error of a specific method, it is necessary to conduct a large number of measurements to collect sufficient statistics. However, as practice shows, this takes too much time. In this regard, a simplification was adopted that the measurement accuracy of the method can be roughly estimated by the proximity of the value of indirectly measured quantities to their theoretical values. Thus, within the framework of the permissible simplification, the criterion for the measurement accuracy of the method for detecting an object in video frames is the relative error of the indirectly measured value in relation to the corresponding theoretical value.

The next indicator that influences the choice of object recognition method in video frames is its performance. In this paper, performance is understood as the processing speed, i.e., the time spent on processing a certain number of video frames by one method or another. Performance plays a major role especially in cases where measurements must be taken in real time.

Finally, the last indicator adopted in this paper and influencing the choice of object recognition method is the indicator "resistance to external conditions". This indicator is a qualitative indicator. It only records the fact of the presence of a dependence of the recognition error and/or the measurement error of the recognition method on certain conditions of the experiment (the presence or absence of artificial lighting, the distance from the camera to the object). Accordingly, the criterion for assessing this indicator is two possible values:

– there is a dependence;

– the dependence is insignificant or absent altogether.

This indicator affects the reproducibility of the experimental results. It is obvious that if the measurement result of a particular physical quantity strongly depends on external conditions, then its reproduction can be very difficult.

A comparison of the recognition error, measurement error, performance, and resistance to external factors of both methods was carried out mainly on the example of calculating the oscillation period of a mathematical pendulum, where it was necessary to detect a spherical body in video frames. Detection of a circle in a video frame using the Hough method was performed using the HoughCircles() function of the OpenCV library in the Python programming language.

The YOLOv8n (Nano) version was chosen as a neural network model, which is the shortest and fastest model. This model is suitable for devices with limited computing resources for designing small systems where maximum video data processing speed is required. Despite its compactness, YOLOv8n retains reasonable accuracy to effectively perform object detection tasks in video frames.

The YOLOv8n model was trained on a computer with an NVIDIA GeForce RTX 3070 Laptop GPU with 8192 MB of video memory. The YOLOv8n model was integrated into a Python program using the Ultralytics library. 2695 images were used for training the model, and 889 images for testing. This amount of data provided a sufficient sample for high-quality training and testing of the YOLOv8n model on new data. The model was trained over 50 epochs.

5. Results of analyzing the efficiency of the method of experimental measurement of physical quantities for educational purposes using computer vision

5. 1. Devising a method for determining the functional type of the law of motion of objects based on video frames using computer vision

The idea of the method for determining the functional type of the law of motion of an object based on video frames is that if there is a reliably determined law of motion in the experiment, then the kinematic characteristics are easily calculated by differentiating this law. To perform differentiation, it is first necessary to determine the functional type of the law of motion. For this purpose, approximation methods of experimental data are used. Fig. 7 shows the basic block diagram of the algorithm for the law of motion of an object based on video frames.

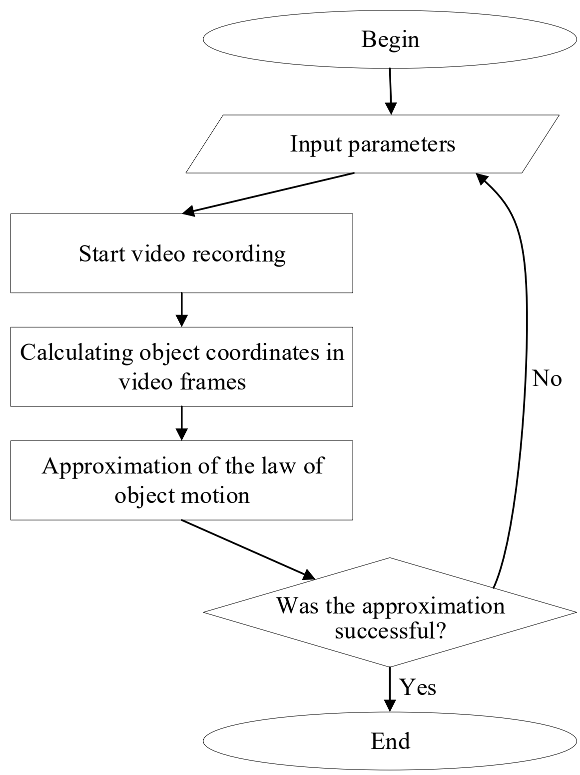

Fig. 7. Generalized block diagram of the algorithm for calculating the kinematic quantities of mechanical motion from video frames

At the "input parameters" stage, the initial data of the experiment are entered. For example, for a mathematical pendulum, the length of its thread, and for the movement of a ball along an inclined plane, the angle of inclination, the radius of the ball, etc. These data are usually required to calculate the theoretical values of the measured characteristics such as the period of oscillation of the pendulum, the moment of inertia of a body rolling along an inclined plane, etc.

Next, a video camera is turned on to record the movement of any body on video. These video frames are then processed using object recognition methods, resulting in a set of discrete data describing the dependence of the object's coordinate on time. Based on this set of discrete data, the corresponding functional form of the law of object motion is determined using approximation. For example, the law of oscillatory motion of a mathematical pendulum with a small amplitude can be described by the following approximating function

$$X(t) = X_0 \sin(\omega t), \quad (1)$$

where X_0 is the amplitude, ω is the cyclic frequency of the pendulum oscillation.

In this case, the instantaneous velocities and accelerations of the pendulum can be determined as follows:

$$v(t) = X_0 \omega \sin(\omega t), \quad (2)$$

$$a(t) = X_0 \omega^2 \sin(\omega t), \quad (3)$$

where $v(t)$ and $a(t)$ are the instantaneous values of velocity and acceleration. If we consider the motion of a ball on an inclined plane without slipping, then it should roll down with a constant acceleration of the translational motion of its center. In the absence of an initial velocity, the law of translational motion of the center of the ball can be described by a quadratic function for approximation

$$X(t) = \frac{at^2}{2}, \quad (4)$$

where a is the acceleration of the translational motion of the center of the ball. Knowing this acceleration, one can calculate many other characteristics of the object and process, for example, the moment of inertia of the ball. The theoretical value of the moment of inertia of a ball, sphere, and cylinder in general can be found using the following formula

$$J = k \cdot mr^2, \quad (5)$$

where m and r are the mass and radius of a ball, sphere, cylinder, etc. The coefficient k, depending on the shape and filling of the body, has a specific value for a specific object. For example, for a homogeneous solid ball, $k = 0$.

Knowing the acceleration of the translational motion of the center of the ball and the angle of inclination of the plane, the coefficient k can be calculated as follows

$$k = \frac{g \sin(\beta)}{a} - 1, \quad (6)$$

where g is the acceleration of gravity, β is the angle of inclination of the inclined plane, a is the acceleration of the translational motion of the center of the ball.

Fig. 8 shows a general view of the user graphical interface designed to conduct an experiment to study the motion of a mathematical pendulum and to demonstrate the results of the approximation.

The interface is organized so that the video that was shot on a video camera is shown in the upper left corner. And in the upper right and lower left corners, the blue dots show the coordinates of the pendulum in the video frames along the abscissa and ordinate, and the red lines are the graph of the approximating sinusoidal function. From Fig. 8, one can see that the experimental data actually exactly correspond to the values of the approximating function. Knowing the approximation function, we can easily determine the oscillation period, which in this case turned out to be equal to approximately 1.002 sec. The data that correspond to the approximation function are shown in the lower right corner.

A similar uniform graphical interface and a common algorithm are used for any experiment. Fig. 9 shows another example related to the study of the motion of a physical pendulum.

Fig. 10 shows a general view of the user graphical interface with an example of processing the movement of a solid ball rolling down an inclined plane.

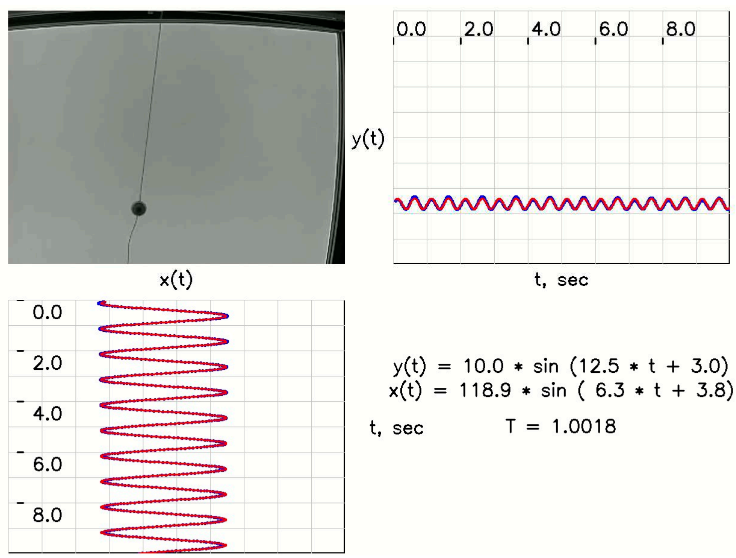

Fig. 8. Measuring the period of oscillation of a pendulum using YOLOv8n with a pendulum length of 25 cm

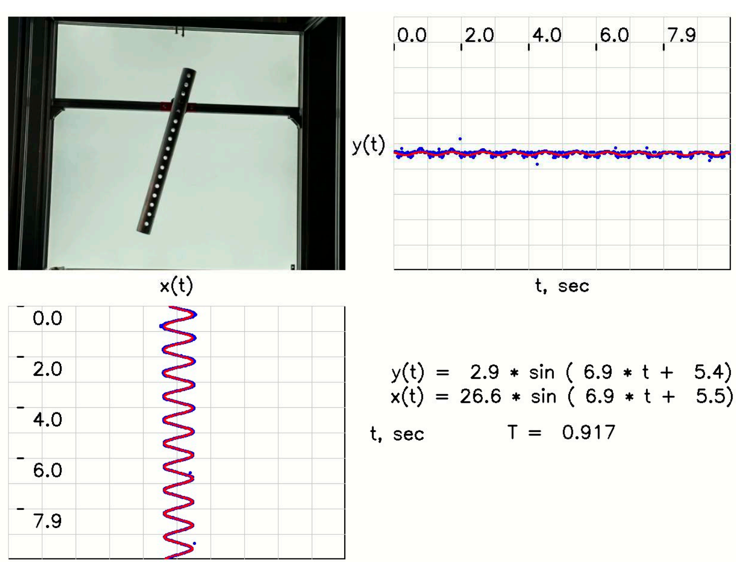

Fig. 9. An example of measuring the oscillation period of a physical pendulum using YOLOv8n with artificial lighting on

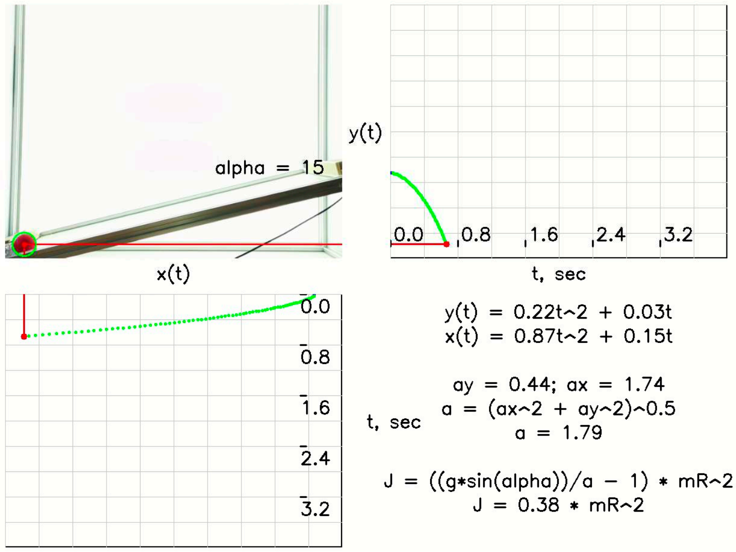

Fig. 10. An example of a user graphical interface that depicts the course of processing the motion of a solid ball rolling down an inclined plane

In Fig. 10, the lower right corner shows the value of the coefficient k calculated using formula (6). The plane tilt angle is 15 degrees. For this case, the coefficient $k=038$. Further, Table 1 gives all values of the coefficient k calculated in this way for different tilt angles for a solid sphere and cylinder.

Table 1

Values of coefficient k at different tilt angles for a solid sphere and cylinder, measured using YOLOv8n

Experiment No.	Angle of inclination, degree	Coefficient k values	
		For sphere	For cylinder
1	6.65	0.42	0.49
2	8.47	0.43	0.51
3	9.70	0.39	0.48
4	10.92	0.38	0.48
5	12.77	0.39	0.49
6	14.63	0.39	0.50
7	15.88	0.40	0.52
Mean value		0,40	0.496

Note that the theoretical values of coefficient k for a solid sphere and a cylinder are 0.4 and 0.5, respectively. We calculate the accuracy of indirect measurement of the coefficient k for a confidence probability of 0.95 and take into account that in this case the Student's coefficient for 7 measurements is 2.365. Then the relative error in measuring the coefficient k of these objects is approximately:

– for a sphere – 4.1%;

– for a cylinder– 2.7%.

In this case, the average value of coefficient k actually coincides with its theoretical values.

5. 2. Selecting the most suitable method for recognizing objects in video frames

To solve this task, a comparative analysis of the recognition error, measurement error, data processing speed, and resistance to external conditions of the Hough and YOLOv8n methods was carried out. For this purpose, a video of the oscillations of a mathematical pendulum lasting 10 seconds with a frame rate of 90 fps was recorded on the video camera of the measurement module running on a Raspberry PI 5 model B microcomputer. The recording was carried out under the following conditions:

– the length of the mathematical pendulum took on different values;

– the camera was located at a small (25–30 cm), medium (38–40 cm), and large (47–50 cm) distances from the pendulum;

– with artificial lighting on and off (Fig. 6).

Thus, there were 901 frames in the 10-second video files. A search for a circle was carried out on these video frames using two methods. It should be noted that in the presence of artificial lighting, both methods, Hough and YOLOv8n, showed a minimum recognition error of approximately 0.1%. However, in natural light during the daytime in the absence of artificial light sources, these methods showed different recognition errors. The result of the experiment on measuring the recognition error of object detection methods in video frames under natural light during daylight hours is given in Table 2.

Table 2

Results of measuring the recognition error by the Hough and YOLOv8n methods in recognizing objects in video frames

Experiment No.	Pendulum length, cm	Distance to camera	Number of frames found by the Hough method	Number of frames found by YOLOv8n
1	15	Small	884	901
2	15	Medium	881	901
3	15	Large	857	900
4	18	Small	890	901
5	18	Medium	885	901
6	18	Large	879	901
7	21	Small	886	901
8	21	Medium	881	901
9	21	Large	875	901
10	24	Small	890	901
11	24	Medium	891	901
12	24	Large	866	892

As can be seen from Table 2, the pendulum length has virtually no effect on the accuracy of the methods. The average recognition error of the Hough method is 2.3%, while that of the YOLOv8n method is 0.1%. Consequently, the YOLOv8n method has a much lower recognition error than the Hough method when conducting experiments in the daytime, in the absence of any artificial lighting.

In the case of the Hough method, it can also be noted that the distance from the camera to the pendulum plays a significant role. The average value of the object recognition error by the Hough method according to Table 2 takes the following values:

– at a short distance – 1.5%;

– at an average distance – 1.83%;

– at a long distance – 3.52%.

The dependence of the recognition error by the Hough method on the distance of the video camera from the object is clearly visible. The further the video camera is from the object, the higher the recognition error. However, such a dependence of the recognition error for the YOLOv8n method is virtually absent. Therefore, it can be argued that the Hough method is less resistant to external conditions than the YOLOv8n neural network method.

According to the adopted simplification described in chapter 4 of this paper, the measurement accuracy of the recognition methods is determined by the correspondence of the measured values of the pendulum oscillation period to its theoretical values, calculated using the Thompson formula

$$T = 2\pi\sqrt{\frac{L}{g}}, \qquad (7)$$

where L is the pendulum length, g is the acceleration due to gravity.

Table 3 gives the theoretical, manually measured, Hough, and YOLOv8n values of the pendulum oscillation periods corresponding to its different lengths. Manual determination of the oscillation period was performed in the standard way, i.e., the time spent on a certain number of oscillations was measured with a stopwatch. This time was then divided by the number of oscillations. The experiments were recorded in daylight at an average distance of the camera from the pendulum.

Table 3

Periods of oscillation of a mathematical pendulum, determined in different ways

Pendulum length, cm	Pendulum oscillation period, s			
	Hough method	YOLOv8n	Manually	Theory
15	0.781	0.778	0.786	0.777
18	0.865	0.853	0.868	0.851
20	0.904	0.895	0.887	0.897
21	0.929	0.921	0.935	0.919
22	0.953	0.938	0.955	0.941
25	1.007	1.002	1.009	1.003
27	1.036	1.041	1.043	1.042

Based on the data in Table 3, the relative average error, the deviation of measured values from theoretical values, was calculated using the following formula

$$\langle \varepsilon \rangle = \frac{1}{n}\sum_{i=1}^{n}\frac{\left|T_{ei} - T_{ti}\right|}{T_{ti}} \cdot 100\%, \qquad (8)$$

where T_{ti} is the theoretical value, T_{ei} is the experimental value of the oscillation period of the mathematical pendulum.

The calculation results according to (8) based on the data from Table 3 showed the following values of the measurement error:

– for the Hough method – 0.9%;

– for the trained YOLOv8n model – 0.2%;

– manual measurement – 1.2%.

In terms of measurement error, the YOLOv8n method again turns out to be outperforming the Hough method.

To calculate the performance of object detection methods in video frames, the following two platforms were considered:

– standard version of the Raspberry PI 5 model B microcomputer;

– personal computer with CPU – AMD Ryzen 7 5800H and GPU – NVIDIA GeForce RTX 3070 with a video memory of 8192 MB.

Recordings of the oscillatory motion of a mathematical pendulum lasting 10 seconds were used as test data to determine the performance of various methods of recognizing objects in video frames. It should be noted that the YOLOv8n neural network method can be run on both CPU and GPU. And the Hough method is executed only on CPU. Table 4 gives the time spent on processing 901 video frames by different methods on a personal computer in order to detect a circle. In this case, the video camera was located at different distances from the pendulum, the length of which was also different.

Table 4

Time taken to detect a circle from 10 seconds of video data on a personal computer using different methods

Experiment No.	Pendulum length, cm	Distance to camera	Time spent on processing, s		
			YOLOv8n on GPU	YOLOv8n on CPU	Hough method on CPU
1	15	Small	9.697	45.480	6.484
2	15	Medium	9.485	46.434	6.418
3	15	Large	9.521	45.276	6.660
4	18	Small	9.380	49.145	6.387
5	18	Medium	9.421	45.273	6.251
6	18	Large	9.492	45.138	6.641
7	21	Small	9.463	45.216	6.291
8	21	Medium	9.410	45.905	6.414
9	21	Large	9.446	45.006	6.802
10	24	Small	9.531	45.209	6.543
11	24	Medium	9.467	46.370	6.432
12	24	Large	9.509	49.114	6.698
Mean value			9.485	46.131	6.502

The following Table 5 gives the time spent on processing 901 video frames using different methods on the Raspberry PI 5 model B platform. This microcomputer does not have a powerful computing video card, so the data is given only for the case of using CPU.

Table 5

Time spent on circle detection from 10 sec video data on Raspberry PI 5 model B platform using different methods

Experiment No.	Pendulum length, cm	Distance to camera	Time spent on processing, s	
			YOLOv8n	Hough method
1	15	Small	88.508	8.737
2	15	Medium	88.564	9.060
3	15	Large	88.201	8.962
4	18	Small	89.373	9.678
5	18	Medium	88.332	8.748
6	18	Large	88.014	8.944
7	21	Small	88.349	8.842
8	21	Medium	88.378	8.782
9	21	Large	88.124	8.992
10	24	Small	88.268	8.794
11	24	Medium	88.129	8.954
12	24	Large	88.143	9.035
Mean value			88.365	8.961

According to the data in Table 5, it is clear that the duration of video processing on the Raspberry PI 5 platform using the Hough method is 10 times faster than the YOLOv8n neural network method.

6. Discussion of results based on analyzing the effectiveness of the method of experimental measurement of physical quantities for educational purposes using computer vision

Our paper considered two different methods of detecting objects in video frames: algorithmic (Hough method) and neural network (based on the YOLOv8n model). A comparative analysis of their recognition error, measurement error, performance and resistance to external conditions was carried out. An approach to indirect measurement of various physical quantities using the law of object motion determined by the Hough or YOLOv8n methods has been proposed.

Firstly, using the example of the data given in Table 1, it can be argued that the proposed method of indirect measurement of physical quantities has a fairly high accuracy. In this example, the error in determining coefficient k of the moment of inertia of the body does not exceed 4.1%. Such high accuracy of indirect measurement of the value of a physical quantity by the proposed method is achieved through the use of advanced technology based on the application of a special neural network model for recognizing objects in video frames. Also, the accuracy of this method is strongly influenced by the decision to approximate the process using the appropriate mathematical functions.

As can be seen from Table 2, the pendulum length has virtually no effect on the accuracy of the methods. The average recognition error by the Hough method is 2.3%, while that of the YOLOv8n method is 0.1%. Consequently, the YOLOv8n method has a much lower recognition error than the Hough method when conducting experiments in the daytime, in the absence of any artificial lighting.

Secondly, according to the data in Table 2, it was established that the average recognition error by the Hough method is 2.3%, and 0.1% for the YOLOv8n method. In addition, the recognition error of the Hough method turned out to be dependent on the presence or absence of artificial lighting and on the distance of the video camera to the object. At the same time, the recognition error by the Hough method, depending on the distance of the video camera to the object, varies from 1.5% to 3.52%. Thus, the YOLOv8n method has a much smaller object recognition error and is more resistant to external conditions than the Hough method.

The results of the calculation using formula (8) based on the data in Table 3 showed that the measurement error of the Hough method is 0.9%, and 0.2% for the YOLOv8n method. And according to this indicator, the YOLOv8n method is also more preferable.

However, measuring the performance of these methods of object recognition on video frames gives the opposite result, where the Hough method is in a much better position. The speed of video processing by the Hough method on the Raspberry PI 5 platform turned out to be 10 times faster than the speed of processing the same video by the YOLOv8n neural network method on the same platform. Thus, where high accuracy of measuring physical quantities is required, YOLOv8n should be used. But in the case where the speed of video data processing is critical, the Hough method with artificial lighting should be used.

Unlike the methods of measuring physical quantities using computer vision suggested in [1–10], our proposed approach has a number of advantages. The main advantage of our approach is that the data is always processed in a uniform way and has a uniform type of graphical user interface. And indirect measurements of physical quantities by the proposed method have a fairly high accuracy. At the same time, it is possible to choose the method of detecting objects in video frames when either high accuracy or high speed is required. It is also possible to control the course of the experiment using various sensors and mechanisms. In addition, this approach makes it possible to broadcast the entire process for online training, from the beginning of the experiment to the end of data processing. The ability to combine measurements and broadcast the process is ensured by using a video camera as a measuring device.

At the same time, our study has a number of limitations. Firstly, it only considered the case of mechanical motion. Accordingly, the result of the study in this form is not suitable for studying other physical phenomena. Secondly, only two methods of detecting objects in video frames were analyzed. Perhaps, using other methods, the results will be completely different.

Among the disadvantages, one can note the need to implement devices on technical means with limited computing resources since conventional powerful personal computers are expensive and it is difficult to control the process online with their help. It is also necessary to take into account that the proposed approach requires specifying the initial type of the law of motion to select the approximating function. This imposes a limitation on the possibility of measuring the kinematic quantities of any spontaneous motion that cannot be described in advance using a specific equation.

Nevertheless, this approach is promising since it easily combines the ability to study some laws of physics both online and in the conventional format. In the future, additional research is required so that this approach can be extended to other areas of physics.

7. Conclusions

1. It has been established that our proposed method of indirect measurement of physical quantities using computer vision has a small error. For example, in the problem of studying the movement of a round body on an inclined plane, the error in measuring the moment of inertia was in the range from 2.7% to 4.1%. The deviation of the average measured period of a mathematical pendulum from the theoretical one was equal to 0.092%. Thus, it can be stated that this method is universal and quite accurate.

2. A comparative analysis of the efficiency of the algorithmic and neural network methods revealed that the neural network method based on the YOLOv8n model has a number of advantages in terms of measurement accuracy. This method is also much more resistant to external conditions than the Hough method. This advantage is especially evident when video recording is done in natural light. The accuracy of the method based on the YOLOv8n model is almost four times higher than the accuracy of the Hough method. At the same time, both computer methods determine the period of a mathematical pendulum much more accurately than the standard manual measurement method using a stopwatch. However, the YOLOv8n neural network method is much inferior to the Hough algorithmic method in terms of performance. Performance measurements of both methods on the Raspberry PI 5 model B platform showed that the Hough method processes video data almost ten times faster than the YOLOv8n method. However, if the YOLOv8n method is run on the GPU, and the Hough method on the CPU of a standard personal computer, in this case the difference in performance is reduced to one and a half times. Thus, to obtain maximum measurement ac-

curacy and acceptable performance, it is necessary to use the YOLOv8n method, performing calculations on GPU.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors used artificial intelligence technologies within acceptable limits to provide their own verified data, which is described in the research methodology section.

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