Smart Pendulum

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Abstract. The project is an automated experimental setup which is intended for measuring the oscillation period of a pendulum. The experiment is largely autonomous and suitable for demonstrations. The pendulum oscillations are registered by a system comprising of a LED and an analog light sensor. The analog signal is digitized using an Arduino microcontroller and sent to a PC, where the data is processed in real time with MS Excel. The period of the pendulum is measured repeatedly with significant accuracy, the statistical distribution is dynamically graphed and values such as the mean and deviation are calculated. Other phenomena which can be demonstrated using the setup are the relation between the pendulum's length and period, and the restrictions for the deviation angle required to achieve harmonic oscillations. The digital processing and dynamic visualization of the data allows for the experiment to be conducted without difficulties. All measurements and results remain mostly independent of the experimenter, which guarantees objectivity and accuracy of the data. It is easy to achieve a large number of measurements with little effort, which makes for a good visualization of the Gaussian distribution of the results. The experimental setup is simple, easy to recreate and all software used is open-source. This affordable and accessible setup is applicable in student laboratories, in schools and for scientific demonstrations.

Keywords: pendulum, harmonic oscillation, period, automated experiment, normal distribution

1. INTRODUCTION

This project is an accessible and affordable automated experimental setup which measures the oscillation period of a pendulum. The experiment is largely autonomous, accurate and has demonstrational and educational value. It is intended mostly for use in student laboratories and for scientific demonstrations.

2. THEORETICAL BASIS

2.1 Simple Gravity Pendulum

A simple gravity pendulum is an idealized mathematical model of a pendulum. It is understood to be composed from a weightless thread or inflexible line with a weight attached to one end (Huygens et al., 1673). When displaced from its equilibrium position, it begins to oscillate. The time for one complete cycle of the oscillations is called the period of the pendulum. In the case of the simple gravity pendulum and as long as the amplitude of the oscillation is small, the period of the system is given by

$$T = 2\pi\sqrt{\frac{l}{g}} \qquad (1)$$

For larger amplitudes, the period becomes a function of the amplitude as well (Nelson & Olsson, 1985).

2.2 Normal Distribution

The normal distribution (Gaussian distribution, the bell curve) is a continuous probability distribution which is often used to represent real-valued random variables.

It occurs naturally in exploration of the probabilities of possible events in many experiments. Particularly, such events are different values of a variable and a variable with a normal distribution is therefore normally distributed (a normal deviate).

Important properties of the normal distribution are that its moments are zero, except for the mean and variance, that it’s completely symmetric and its median and mode equal the mean (Feller et al., 1968).

The probability density of the normal distribution is

$$f\left(x_i\right)=\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{\left(x_i-\mu\right)}{2\sigma^2}} \qquad (2)$$

where μ is the mean, σ – the standard deviation (a measure of how dispersed the data values are) and σ^2 – the variance (the expectation of the squared deviation of a variable from its mean), respectively.

The standard (when the variable is expressed in terms of standard units $\frac{x-\mu}{\sigma}$) normal distribution function is given by its integral

$$N(x)=\frac{1}{2\pi}\int_{-\infty}^{x}e^{-\frac{1}{2}y^2}dy \qquad (3)$$

For a sample of finite size, the mean is given by the arithmetic mean of its elements

$$\bar{x}=\frac{\sum_{i=1}^{N}x_i}{N} \qquad (4)$$

and the standard deviation of the sample is

$$\bar{x}=\sqrt{\frac{\sum_{i=1}^{N}(x-\bar{x})^2}{N-1}} \qquad (5)$$

(Spiegel & Stephens, 1992).

3. METHODOLOGY

3.1 Hardware

The experimental setup’s construction includes:

- A simple gravity pendulum - a high wooden stand (built up by blocks), a long string with a weight (a ball) at its end (Fig. 3, (2));

A two-point suspension system is used in order to restrict the oscillations to a single plane and to reduce the amount of errors, imported by the non-planar movement by reducing the number of degrees of freedom.

The construction allows the experimenter to easily change the height of suspension and the length of the string, which is made possible by additional holes throughout the height of the block and an easy dismantlement procedure.

- A detection system for the pendulum’s passing past its lowest point - a monochromatic light emission diode with 630 nm wavelength (Fig. 3, (1)), an analog light sensor ALS-PT19 (Fig. 3, (3)), an Arduino Uno microcontroller board (Fig. 3, (4)), a computer (Fig. 3, (5))

The LED and the sensor are centered and aligned against each other at a height equal to the pendulum’s lowest passing point, thus the registration of the decreasing light flow is rendered highly accurate. The data collected by the sensor is sent to a PC through the Arduino microcontroller board.

The experimental setup can be recreated with any similar hardware construction, as long as the passing of the pendulum between the LED and the light sensor is ensured. Additionally, the measurement methodology can easily be adapted for other oscillatory systems such as a spring-mass system, a spring pendulum, etc.

Fig. 1 Experimental setup

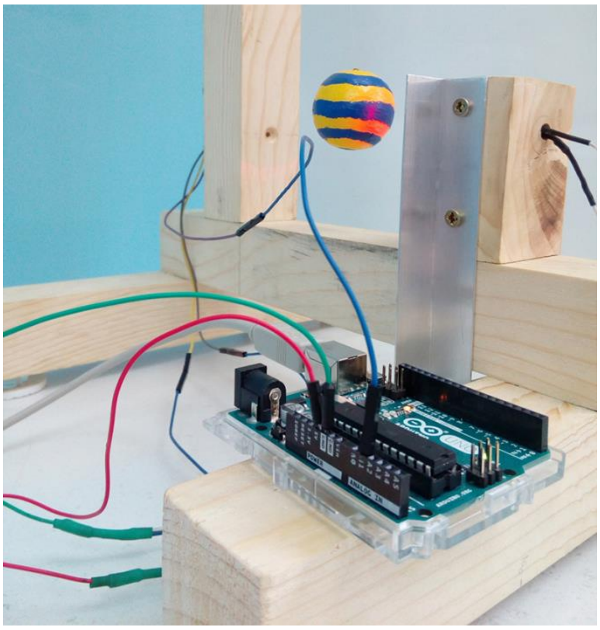

Fig. 2 Arduino Uno microcontroller and detection circuit

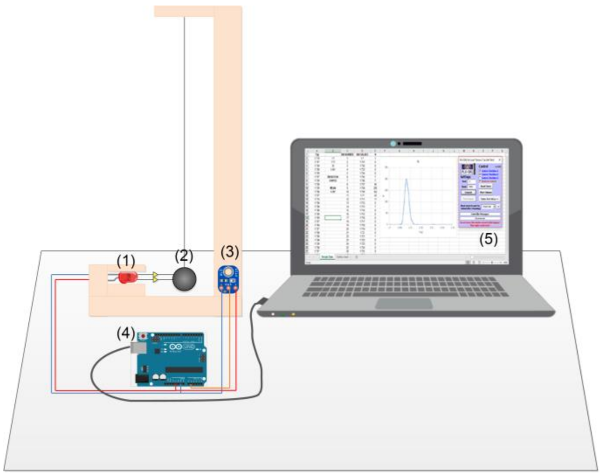

Fig. 3 Experimental setup: (1) – LED emitting monochromatic light at 630 nm; (2) – pendulum blocking the light to the sensor; (3) – analog light sensor; (4) – Arduino Uno microcontroller, detecting the times of increasing fronts, calculating period and sending data to the computer; (5) – computer with MS Excel, where the data is dynamically processed

3.2 Software

The analog signal from the ALS-PT19 light sensor (Fig. 3, (3)) is received by Arduino Uno microcontroller (Fig. 3, (4)). The digitized signal is then sent through an USB cable to a PC (Fig. 3, (5)), where the data is transferred to an MS Excel spreadsheet and dynamically processed.

The Arduino code is written in the Arduino IDE. The connection between the serial port and MS Excel is realized via PLX-DAQ. PLX-DAQ is an open-source Parallax microcontroller data acquisition add-on tool for Microsoft Excel.

Immediately after the sketch is uploaded to the microcontroller, the sensor begins collecting data for the automatic calibration. The lowest and highest light levels registered in the first five seconds are logged into the program. After that, the middle level of light is calculated. By performing this calibration, the experiment is not dependent on the external light conditions.

The period of the pendulum is calculated using the inner timer of the Arduino microcontroller. The signal received from the sensor has the shape of a periodic rectangular function. The rising and decreasing fronts indicate the passing of the pendulum through its equilibrium position. By registering the timer states at the points of identical fronts and calculating the difference between them, the period is measured in milliseconds.

The values of the period in seconds are sent to MS Excel. Using the function FREQUENCY, the data is distributed in bins. The mean and deviation are dynamically calculated each time new values are received. The frequency distribution of the experimental data is also dynamically plotted.

The method of measurement is simple and accurate. The external light conditions and the asymmetry of the sensor and LED position in relation to the pendulum do not affect the results. A large number of measurements are easily and quickly carried out, which ensures the statistical credibility of the data.

4. EXPERIMENTAL RESULTS

It is easy to obtain a large volume of data quickly. Examples are given with 500 measurements at different lengths of the pendulum in Fig. 4 – Fig. 7.

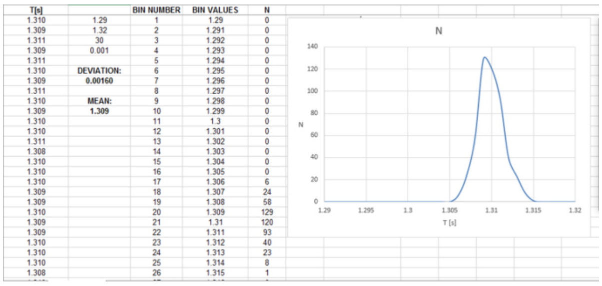

Fig. 4 Results of 500 measurements at pendulum length 43 cm

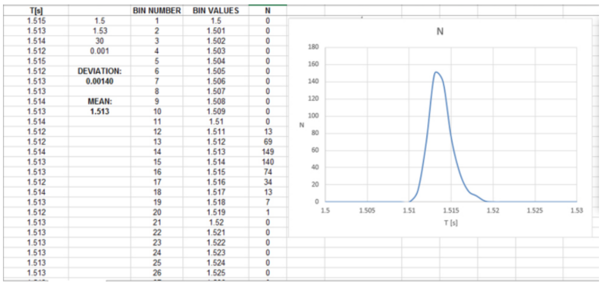

Fig. 5 Results of 500 measurements at pendulum length 56,9 cm

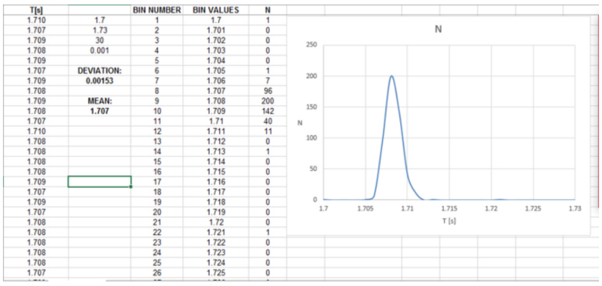

Fig. 6 Results of 500 measurements at pendulum length 73 cm

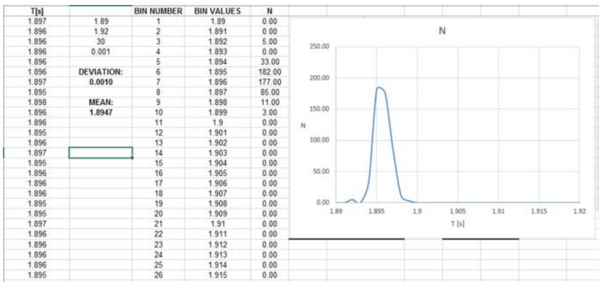

Fig. 7 Results of 500 measurements at pendulum length 89,2 cm

5. APPLICATIONS

The experimental setup is mainly intended for use in student laboratories.

It can be used for demonstrations in schools to display the relation between the pendulum’s length and its period, the conditions for realizing harmonic oscillations and the statistical distribution of the data.

It is also suitable for an educational experiment in student laboratories. An otherwise slow and laborable experiment is almost completely automated, so hundreds of measurements can be carried out quickly and easily.

In conclusion, the experimental setup has demonstrational and educational value, allowing for automated visualization of physical and statistical laws.

ACKNOWLEDGEMENTS

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Arduino Uno: *https://www.arduino.cc/*

PLX-DAQ: *https://www.parallax.com/downloads/plx-daq*

SciTeam: *http://phys.uni-sofia.bg/~zoggy/sciteam/*