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Scientific articles

Ciencia para todos: Diseño y validación de un dispositivo de bajo costo y código abierto para estudiar la caída libre

Science for all: Design and validation of a low-cost, open-source device to study free fall

Ciência para todos: Projeto e validação de um dispositivo de baixo custo e código aberto para estudar a queda livre

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Resumen

La enseñanza de la física requiere herramientas experimentales asequibles. Frente al alto costo de los dispositivos comerciales, este estudio propone y valida un dispositivo didáctico de alta precisión basado en impresión 3D y plataforma Arduino para medir la aceleración de la gravedad. El sistema controla la caída de un balón metálico desde un electroimán hasta una base con sensor piezoeléctrico. Se construyeron cinco unidades con 80 mediciones por dispositivo (10 por ocho alturas entre 20 cm y 90 cm). Se realizaron estudios de repetibilidad y reproducibilidad. Los dispositivos resultaron estadísticamente equivalentes con errores porcentuales inferiores al 0.42% respecto al valor teórico local y coeficientes de determinación de 1.00. La exactitud supera la de modelos similares en la literatura. El costo de fabricación fue de una tercera parte del equipo comercial más barato del mercado. Se concluye que el dispositivo es una herramienta accesible y precisa, cuyo diseño modular además permite integrar nuevos experimentos. La liberación del diseño bajo licencia Creative Commons democratiza el acceso a equipamiento científico de calidad.

Palabras clave: Arduino, enseñanza de la física, equidad educativa, impresión 3D, objetivos de desarrollo sostenible, repetibilidad y reproducibilidad

Abstract

The teaching of physics requires affordable experimental tools. Faced with the high cost of commercial devices, this study proposes and validates a high-precision didactic device based on 3D printing and the Arduino platform to measure the acceleration of gravity. The system controls the fall of a metal ball from an electromagnet to a base with a piezoelectric sensor. Five units were built with 80 measurements per device (10 for each of the eight heights between 20 cm and 90 cm). Repeatability and reproducibility studies were conducted. The devices were found to be statistically equivalent with percentage errors below 0.42% with respect to the local theoretical value and coefficients of determination of 1.00. The accuracy surpasses that of similar models in the literature. The manufacturing cost was one-third of the cheapest commercial equipment on the market. It is concluded that the device is an accessible and precise tool, whose modular design also allows for the integration of new experiments. Releasing the design under a Creative Commons license democratizes access to quality scientific equipment.

Keywords: Arduino, physics education, educational equity, 3D printing, sustainable development goals, repeatability and reproducibility

Resumo

O ensino de física requer ferramentas experimentais acessíveis. Diante do alto custo dos dispositivos comerciais, este estudo propõe e valida um dispositivo didático de alta precisão baseado em impressão 3D e na plataforma Arduino para medir a aceleração da gravidade. O sistema controla a queda de uma esfera de metal de um eletroímã para uma base com um sensor piezoelétrico. Foram construídas cinco unidades, com 80 medições por dispositivo (10 para cada uma das oito alturas entre 20 cm e 90 cm). Foram realizados estudos de repetibilidade e reprodutibilidade. Os dispositivos mostraram-se estatisticamente equivalentes, com erros percentuais inferiores a 0,42% em relação ao valor teórico local e coeficientes de determinação de 1,00. A precisão supera a de modelos similares na literatura. O custo de fabricação foi um terço do equipamento comercial mais barato do mercado. Conclui-se que o dispositivo é uma ferramenta acessível e precisa, cujo design modular também permite a integração de novos experimentos. A liberação do design sob uma licença Creative Commons democratiza o acesso a equipamentos científicos de qualidade.

Palavras-chave: Arduino, ensino de física, equidade educacional, impressão 3D, objetivos de desenvolvimento sustentável, repetibilidade e reprodutibilidade.

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Introduction

Experimentation promotes active and meaningful learning (Di Bella-Nava et al., 2019), since interacting directly with physical phenomena allows for a deeper understanding than a purely theoretical approach (Solis et al., 2021). This experimental approach is especially relevant for developing critical skills in future scientists and engineers, both in academic and professional settings. In this context, the study of free fall is fundamental, as it provides a solid foundation for understanding the basic principles of classical mechanics. This phenomenon, although seemingly simple, has profound implications for the analysis of a wide range of everyday and complex physical phenomena.

In many educational settings, access to specialized equipment remains limited due to the high cost of technologies such as high-precision digital timers, photogates, or advanced kinematic data acquisition systems.



This research was guided by Sustainable Development Goal 4, which aims to ensure inclusive, equitable, and quality education (UN, 2025). This work proposes the design and construction of a modular, accessible, and open-source educational device based on Arduino and 3D printing. This device allows for the measurement of gravitational acceleration through the precise detection of an object's free-fall time.

The device's design offers a simple solution that facilitates scientific experimentation in the classroom, allowing students to explore fundamental concepts such as uniformly accelerated rectilinear motion and calculate the local acceleration due to gravity. The device uses a metal ball bearing as the test object, held by an electromagnet controlled by a button. Upon release, the ball bearing begins its free fall, which is controlled by an Arduino UNO-compatible programming board that activates a timer. The fall time is recorded until the ball bearing impacts a platform equipped with a piezoelectric sensor, at which point the timer stops. Initially, the method of Juvinao Moyano (2018) for detecting the fall using a vibration sensor was tested, but it proved highly unstable, requiring continuous manual resets.

The device's interface is intuitive, allowing students to release the ball bearing with the push of a button and view the fall time on a screen, simplifying the experimental process. This design is accessible and adaptable to different educational needs, fostering innovation and hands-on learning. The use of sensors and actuators enables precise measurements, bringing the experiments closer to professional standards.

This work aims to develop a high-precision, reproducible device for measuring gravitational acceleration at an affordable cost, enabling educational institutions with limited financial resources to build their own high-quality devices at an affordable price. Therefore, this study seeks to answer the question: Is it possible to build a low-cost device that measures gravitational acceleration with an accuracy greater than 1% and whose results are repeatable and reproducible by different users?

Literature review

Previous efforts to develop cost-effective educational experimentation have focused on two methods: sensors integrated into smartphones and programmable electronic platforms within the Arduino environment.

Smartphones can integrate accelerometers that allow for measuring fall time and calculating gravitational acceleration. Recent research, such as that by Marte et al. (2024) , Vogt and Kuhn (2012), and Martín-Ramos et al. (2017), has measured gravitational

acceleration as $9.27 \pm 0.24 \text{ ms}^{-2}$, $10.0 \pm 0.2 \text{ ms}^{-2}$, and $9.86 \pm 0.06 \text{ ms}^{-2}$ (after calibration), respectively. The accuracy of these devices depends on the quality of the sensors, which introduces a bias based on the students' financial resources.

The other approach is the use of electronic boards. Provasi et al. (2021) used a horizontal launcher and sound sensors, but instead of calculating acceleration directly, they used its theoretical value to calculate the height and compared it with the experimental value, resulting in an error of 6.38%. Moya-Molina (2020) used an ultrasonic sensor to measure the fall of a disc. The sensor measured the distance at regular intervals until impact, obtaining acceleration values between 9.88 ms^{-2} and 10.17 ms^{-2} , without specifying the experimental error.

A widely used method involves attaching a metal ball bearing to an electromagnet and releasing it via programming. Harnsoongnoen et al. (2024) used a smartphone's sound sensor to detect the ball bearing's fall time, obtaining a result of 9.8274 ms^{-2} . Juvinao Moyano (2018) combined an ultrasonic sensor, an electromagnet, and a vibration sensor, but his focus was solely on involving students in its construction, without reporting any experimental accuracy results.

García-Cruz (2016) presented a model with an electromagnet and infrared sensors. He did not offer experimental results, suggesting only its use in the classroom. Casaburo (2021) used a similar Arduino-based system with an electromagnet, employing an infrared emitter-receiver pair. Instead of varying the drop height, this system modified the position of the infrared sensors to simulate different heights. The results of this work showed an acceleration of $9.76 \pm 0.70 \text{ ms}^{-2}$, without specifying how the error was calculated.

El Hadi et al. (2020), published before Casaburo (2021), is an equivalent but improved version. It employed 10 fixed proximity sensors along the fall trajectory. The fall time was measured between each pair of sensors, allowing for multiple measurements during the same fall. This approach improves accuracy by increasing the amount of data, although it limits variability in height, reducing the possibilities for modification. Acceleration was obtained through quadratic regression, yielding a result of 9.86 ms^{-2} , although the experimental error was not documented.

El Hadi et al. (2020) and Casaburo (2021) mention supplementary material, although only the former provides a link, which is unavailable, limiting its accessibility and hindering reproducibility. Furthermore, neither author documents the exact number of measurements. From the texts, it can be inferred that Casaburo (2021) used five different heights without

repeating measurements, and that El Hadi et al. (2020) measured times for nine heights, without knowing if there were repetitions, potentially affecting the accuracy and reliability of their results.

Torres (2023) presented an electromagnet and impact sensor model with automatic height variation and ball bearing loading via stepper motors, simplifying operation but reducing user involvement. Although Torres documents the local acceleration as 9.78 ms^{-2} , he does not provide the experimental acceleration, only presenting the times obtained from 10 measurements per height (five heights between 40 cm and 120 cm). From his documented times, an experimental acceleration of 9.35 ms^{-2} was calculated.

No official precision values were found for commercial brands, but Bu Sinnah and Muhammed (2022) used a commercial device (brand not mentioned) for infrared measurement at heights of 30 cm to 90 cm. Using the mean of three measurements and linear regression on the square of the time, they obtained 9.55 ms^{-2} .

Horvat and Jecmenica (2016) present a unique experimental design: they avoid the use of electromagnets or infrared sensors, employing a mechanical system based on a wire that breaks to release the ball bearing. Their measurements are not limited to varying the height; they also consider the ball bearing's diameter, thermal variations, manufacturing errors, and air resistance. They are the only ones who calculate the acceleration using two methods: averaging and least squares fitting, obtaining values of 9.804 ms^{-2} and 9.798 ms^{-2} , respectively. The value obtained by averaging, compared to the local value calculated as $g_l = 9.8066 \text{ ms}^{-2}$, yields an error of 0.03%, a precision superior to any other experiment reviewed in the literature. The precision improves by not introducing electromagnets, but the use of a wire that must be cut limits the rapid execution of multiple measurements.

The preliminary analysis identifies several areas of opportunity to improve didactic experimentation:

- Continuous variation of height: Many studies limit measurements to fixed heights, restricting the possibility of exploring different conditions.
- Alternative methods to infrared sensors: These have precision limitations due to the distance to the object and the speed of passage of the ball (Mukhopadhyay et al., 2018) and require exact alignment between object and sensor (Casaburo, 2021).
- Robust statistical analysis: It is essential to perform a more rigorous analysis of the measurements, with special emphasis on calculating uncertainties, to ensure the reliability of the results.

- Accessibility and reproducibility: Materials must be affordable and readily available. Construction and usage instructions must be openly accessible to facilitate reproducibility.
- High-precision measurements: It must be demonstrated that the reproduced devices will produce repeatable, high-precision results.
- Construction cost documentation: A clear cost estimate should be provided, especially for institutions with limited budgets.
- R&R (Reproducibility and Repeatability) studies: It is necessary to demonstrate that the measurements are consistent and that the devices can be reproduced and produce consistent measurements again. This is something that none in the literature currently performs.

Theoretical Framework

Galileo Galilei demonstrated that, in the absence of air resistance, all bodies fall with the same acceleration, regardless of their mass. The use of vacuum chambers allows this phenomenon to be verified with precision. However, given the high cost of vacuum equipment, a metal ball bearing was chosen instead, which minimizes the effects of air resistance when falling from small heights.

To calculate the acceleration due to gravity in a vertical rectilinear motion from rest, the following formula was used (Serway and Jewett, 2018) :

$$g(h, t) = \frac{2h}{t^2} \quad (1)$$

Where:

- g is the acceleration due to gravity,
- h is the height from which the body falls,
- t is the fall time.

Textbooks (e.g., Serway and Jewett, 2018) cite a theoretical value for the acceleration due to gravity of 9.81 ms^{-2} , leading to its use in many educational institutions. However, this value is not constant. The acceleration depends on the altitude and latitude of the location (Shi et al., 2021).

To calculate the local acceleration due to gravity, the standard formula is used, which considers the latitude and altitude of a specific location. The formula is as follows (National Metrology Center, 2016):



$$g_l = g_E \cdot (1 + b_1 \cdot \text{sen}^2(\phi) - b_2 \cdot \text{sen}^2(2\phi)) - 3.086 \times 10^{-6} \cdot H \quad (2)$$

Where

g_l is the local acceleration due to gravity

g_E is the acceleration due to gravity at the equator, at sea level (9.780318 ms⁻²)

ϕ is the latitude in degrees

H is the altitude of the place in meters

$b_1 = 0.0053024$ and $b_2 = 0.0000058$ are geophysical constants

The Mexican city of Zacatecas has an altitude of 2423 meters and a latitude of 22.7761 degrees (National Institute of Statistics and Geography, 2021). The calculated value of the local acceleration due to gravity is $g_l = 9.780583866 \text{ ms}^{-2}$. The uncertainty associated with the formula is 0.01% (National Center for Metrology, 2016), so five significant figures is the maximum possible precision and the theoretical reference value is $g_l = 9.7806 \text{ ms}^{-2}$.

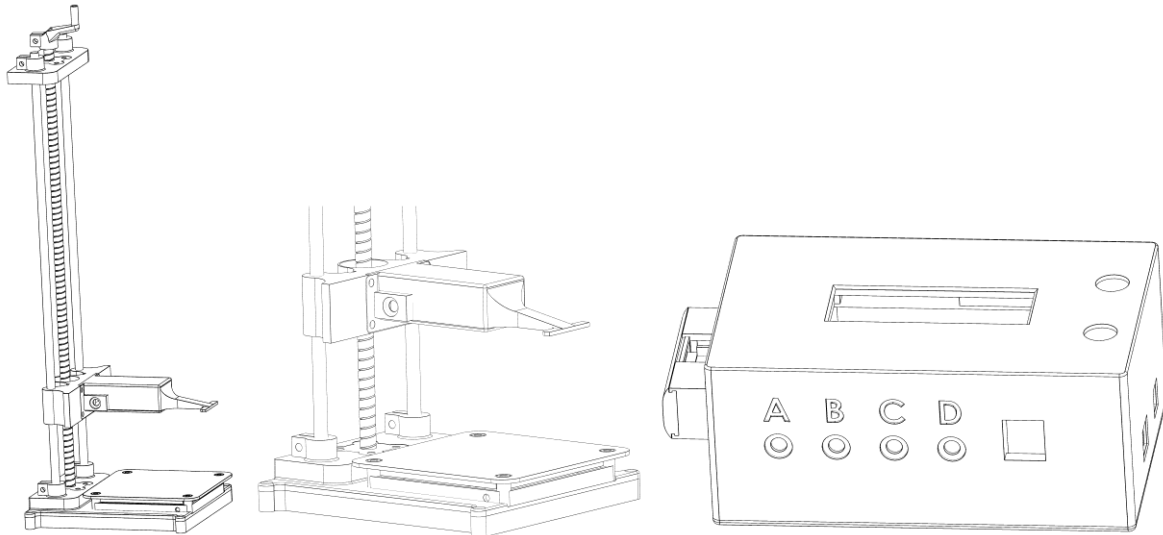
Materials and methods

Device

The device incorporates the most useful features of the prototypes described in the literature, using a generic Arduino UNO compatible data acquisition board with a 12 MHz quartz crystal and a ZYE-P25/20 model electromagnet of 12 VDC at 0.33 A. A metal ball is used as a test object and its fall time is measured with a piezoelectric sensor that detects the impact of the ball on the base.

The mechanical design (Fig. 1a) for raising and lowering the electromagnet uses two smooth metal bars as support guides and a 3D printer worm gear. A crank and lead screw allow the electromagnet to be raised and lowered as needed. The guides are attached to a 7 mm thick rectangular plate, which acts as a counterweight to stabilize the mechanism. The plate is pressed between a base and a cover, which, with the help of supports, maintains a fixed distance between the vertical components. The electromagnet housing has a horizontal extension aligned with its base, allowing the height to be measured with a tape measure.

Figure 1 Device for measuring the acceleration due to gravity in free fall. a) Height variation system (left), b) Detail of the mounted piezoelectric module (center), c) Data processing box (right)

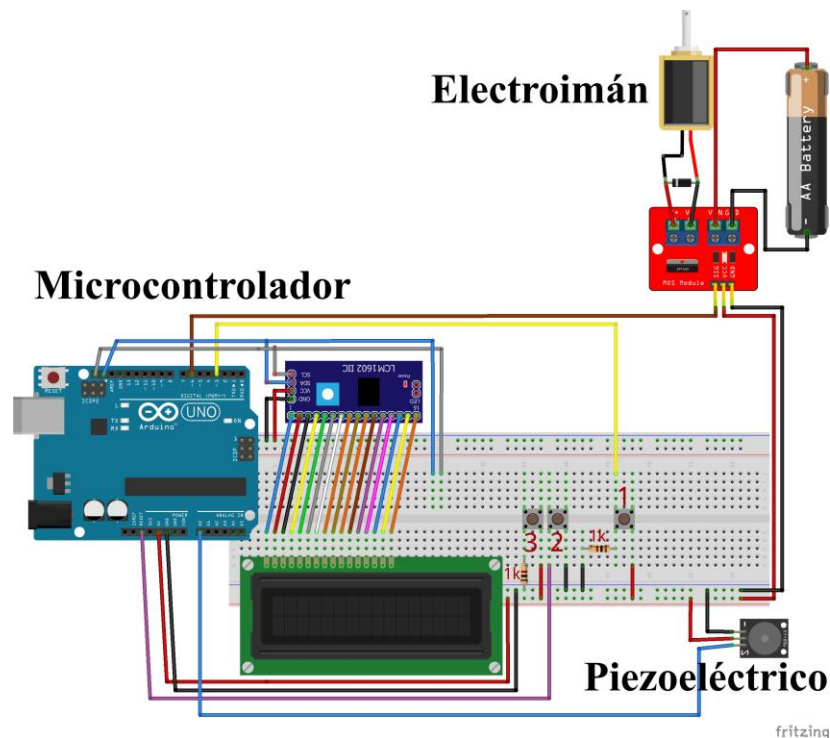


Source: Own elaboration

The piezoelectric sensor is mounted on a base (Fig. 1b) with a movable platform that protects it and promotes uniform measurements. This platform includes a rubber cushioning pad. An electronic module converts the piezoelectric pulse into a digital signal that can be processed by the development platform.

The platform controlling the electromagnet and piezoelectric element is housed within a data processing box (Fig. 1c), which includes activation buttons, data upload ports, and an LCD screen. In the current device, ports A and B are used to connect the electromagnet and piezoelectric element, while ports C and D are available for future modular expansion. Figure 2 shows the electronic schematic, which includes a microcontroller programmed in Arduino IDE 2.3.6.

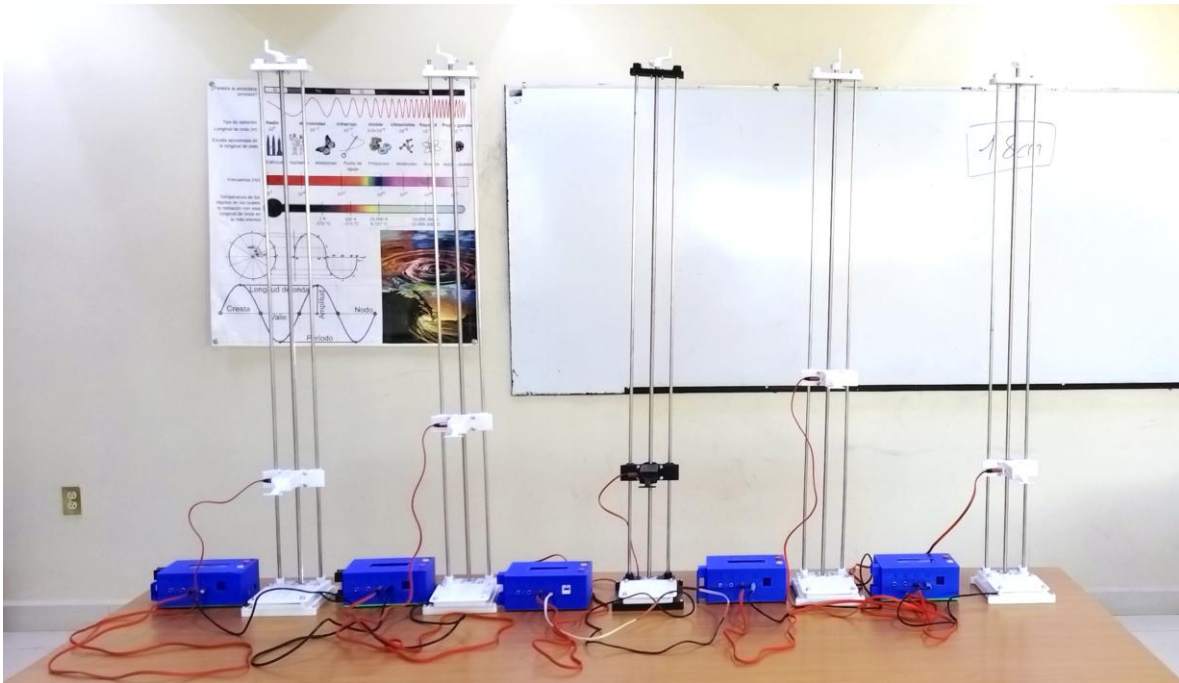
Figure 2. Electronic schematic of the device



Source: Own elaboration

The cost of construction will depend on local availability and the specific components used, but in this study it was approximately \$89 USD: \$10 USD for PLA, \$2 USD for electricity, \$35 USD for electronic and electrical materials and batteries, and \$42 USD for metal rods. Commercial devices ranged from \$293 USD to \$797 USD at the time of reporting.

The designed device also has the advantage of being modular, allowing for the future addition of new experiments. The five devices built for this study are shown in Figure 3.

Figure 3. Devices constructed

Source: Own elaboration

Calibration

To calibrate the device, 100 measurements were taken for each height, from 10 cm to 90 cm in 10 cm increments, on the first device constructed. The 10 cm measurements were discarded due to the high variability caused by the extremely short measurement times, which amplified the relative effect of errors.

The most experienced author performed the measurements. The height was measured from the base of the piezoelectric platform to the surface of the electromagnet. The diameter of the ball bearing was measured with a digital vernier caliper as 1.913 cm, a value that was subtracted from the measured heights.

Errors in time measurement include instrumental errors and associated delays, data processing speed, programming pauses, demagnetization time, and piezoelectric pressure distance.

A critical aspect is the demagnetization time, which is due to a phenomenon called hysteresis: the conservation of magnetic property after external stimulation ceases (Song et al., 2018).

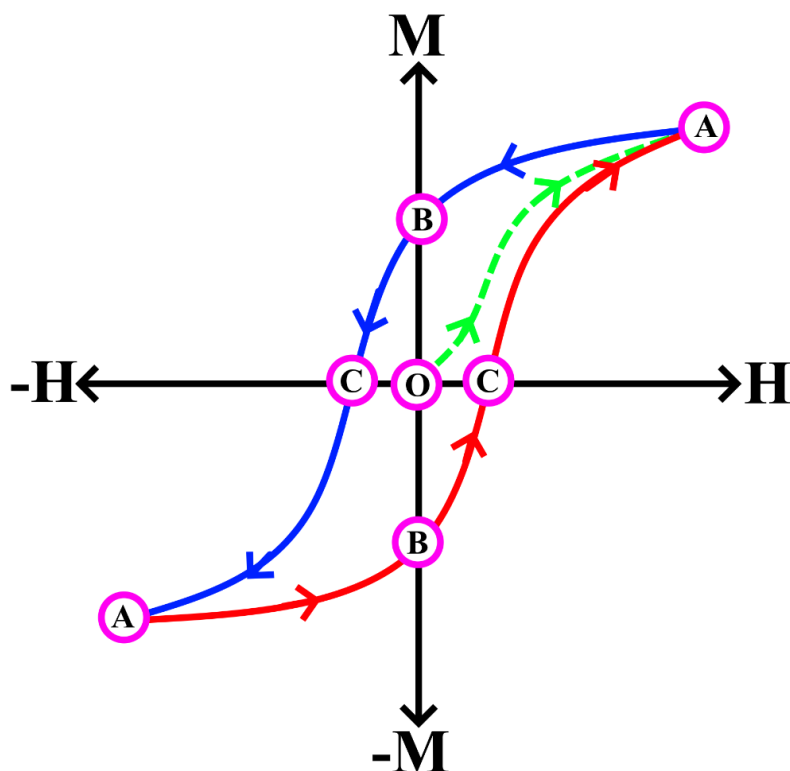
Casaburo (2021) recommends consulting the electromagnet's data sheet or contacting the manufacturer. However, no data sheet includes this information, and obtaining a response from the manufacturer is unlikely.

To better understand hysteresis, we have Figure 4. H is the magnetic field strength and M is the magnetization. Initially, both are at zero (O), but they increase when the electromagnet is switched on (green curve) until they reach a stable maximum. This is the magnetic saturation point (A), and it occurs when the magnetic domains are aligned. If the electromagnet is switched off, H drops to zero (blue curve), but the magnetization does not disappear; instead, it maintains a certain value called remanence (B). To bring M to zero, it is necessary to reverse H to the coercive value (C). If the electromagnet were switched off at this value, the system would be reset to O with no remanence. However, controlling this with the necessary precision is extremely difficult. If H is not stopped in time, the system reaches a new, opposite saturation point. By changing the direction of H , the system follows the red curve, completing the hysteresis cycle.

Waiting for the system to demagnetize on its own is not feasible, especially considering that the process is nonlinear (Song et al., 2018). The alternative was to experimentally find a saturation point high enough to hold the ball bearing, but with minimal remanence. This depends on multiple factors, such as the weight of the ball bearing, the electromagnet model, and the applied voltage.

For the pellet and electromagnet used, it was observed using a variable power supply that the system functioned optimally between 3.5 V and 4.5 V. The value was set at 3.7 V to facilitate its subsequent use with rechargeable batteries of this value.

Figure 4. Typical hysteresis curve



Source: Own elaboration

To fix systematic errors, theoretical times were compared with 800 measurements taken between 20 cm and 90 cm (100 per height). The times showed an average deviation of 2,160 ms, with a standard deviation of 1,039 ms. All devices were calibrated to report a fall time 2,160 ms lower than the measured time.

The 2.160 ms does not represent experimental error, but rather a systematic correction parameter. The experimental error is the standard deviation of 1.039 ms. The length error is taken as the instrumental error of the measuring tape (1 mm). It should be acknowledged that other errors exist that are difficult to quantify, such as parallax error and human error.

Calculations of the acceleration due to gravity

The acceleration was calculated using two methods: arithmetic mean and least squares.

Method of averages

To calculate gravity, 80 experimental values were calculated using equation (1). Error propagation was performed according to Hidalgo and Medina (2008), resulting in:

$$\delta g_i = \sqrt{\left(\frac{4h}{t^3} \delta t\right)^2 + \left(\frac{2}{t^2} \delta h\right)^2} \quad (3)$$

Where δg_i is the error associated with each measurement, $\delta h = 1 \text{ mm}$ and $\delta t = 1.039 \text{ ms}$.

The acceleration for each device is the average of the 80 measurements. The standard error in free-fall measurements tends to be normally distributed (Coluci et al., 2013), so its estimated associated standard error (Walpole et al., 2012) is:

$$\delta g = \frac{\overline{\delta g_i}}{\sqrt{n \cdot m}} \quad (4)$$

Where δg is the total standard error, $\overline{\delta g_i}$ is the average of the individual errors, $n = 10$ (repetitions per height) and $m = 8$ (number of heights).

Quadratic regression method

The average times were fitted by least squares to a quadratic model without a linear or independent term ($h(t) = At^2$), which corresponds to the initial conditions of rest.

The propagation of errors in this case turns out to be

$$\delta g = 2 \sqrt{\left(\frac{\sum_{i=1}^8 \bar{t}_i^2}{\sum_{i=1}^8 \bar{t}_i^4} \delta h\right)^2 + \left(\frac{(\sum_{i=1}^8 2h_i \bar{t}_i)(\sum_{i=1}^8 \bar{t}_i^4) - (\sum_{i=1}^8 4\bar{t}_i^3)(\sum_{i=1}^8 h_i \bar{t}_i^2)}{(\sum_{i=1}^8 \bar{t}_i^4)^2} \delta \bar{t}\right)^2} \quad (5)$$

Where δg it is twice the error associated with A (because the acceleration is twice A), $\delta \bar{t} = 1.039 \text{ ms} / \sqrt{10} \approx 0.329 \text{ ms}$ because it is the average of the errors), and $\delta \bar{h} = 1 \text{ mm}$ (the average formula does not apply because the height was only measured once for each data set).

The coefficient of determination was calculated according to the methodology documented by Walpole et al. (2012).

R&R Studies

Literature on similar devices typically reports a single device with few measurements, without guaranteeing repeatability or reproducibility. To address this gap, repeatability and reproducibility (R&R) studies were conducted.

In addition to the original device (D0), four more were built following the procedure shown in the open access documents (see File Availability) using the calibration obtained

from D0. It is recommended to perform a calibration process when the device is reproduced (see Limitations).

Ten measurements were taken for each height (from 20 cm to 90 cm) on each of the five devices. The measurements for D0 were taken again by the same author who performed the calibration measurements. The other two authors jointly performed the measurements for devices D1 and D2. Since the device is intended for use by students, the measurements for D3 and D4 were taken by high school students who also assisted in the construction of the metal supports for the devices (see Acknowledgments).

To determine the statistical equivalence of the devices, a one-way analysis of variance (ANOVA) was performed on the accelerations obtained. The validity of the method was further validated using Levene's and Tukey's tests. These analyses were performed in R v4.4.2.

The null hypothesis (H_0) is that the means of g are equal:

$$H_0: \mu_0 = \mu_1 = \mu_2 = \mu_3 = \mu_4$$

The alternative hypothesis (H_a) is that at least one device has a different mean.

The analysis used individual acceleration calculations (formula 1).

Results

Table 1 presents the results rounded to two decimal places. The values of g and their errors were calculated using two methods: arithmetic mean and least squares fitting.

Table 1. Acceleration due to gravity calculated by the means method and quadratic regression for the five devices

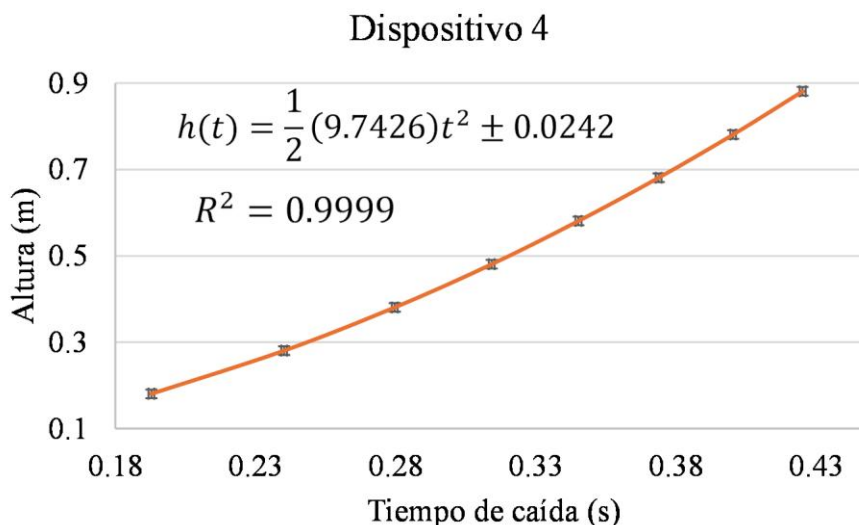
		Device				
		D0	D1	D2	D3	D4
Socks	g (ms^{-2})	9.78	9.77	9.77	9.78	9.74
	EE (ms^{-2})	0.01	0.01	0.01	0.01	0.01
	EP (%)	0.01	0.06	0.15	0.02	0.42
	OF (ms^{-2})	0.01	0.01	0.02	0.01	0.01
Least squares	g (ms^{-2})	9.78	9.77	9.76	9.78	9.74
	EE (ms^{-2})	0.02	0.02	0.02	0.02	0.02
	EP (%)	0.04	0.09	0.21	0.03	0.39
	R^2	1.00	1.00	1.00	1.00	1.00

Source: Own elaboration

Note. g: Calculated acceleration due to gravity, SE: Experimental error, DE: Standard deviation, EP: Percentage error, R²: Coefficient of determination

Figure 5 shows the least squares approximation using data from D4, which had the highest error level. The error bars and the fit are shown in the graph.

Figure 5. Least squares fit for D4 with standard error bars



Source: Own elaboration

Discussion

The acceleration values show high consistency across devices, with very low percentage errors. In the mean calculation, the standard deviations are minimal, indicating high precision. The experimental error is consistent, suggesting a robust and reliable system.

According to Taylor (1997), cited by Marte et al. (2024), and Shigley (1993), cited by Torres (2023), errors below 1% or 2% are acceptable. The greatest variation among the five devices occurred in D4, with a percentage error of 0.42%.

The least squares adjustment yielded similar results, with differences between both methods less than 0.01 ms⁻² and almost perfect coefficients of determination (R²), suggesting that random errors do not have a significant impact.

The repeatability and reproducibility (R&R) analysis using ANOVA shows no statistically significant differences between the devices ($F(4,395) = 0.630, p = 0.641$), confirming their equivalence. Tukey's post hoc test reinforces this equivalence ($p = 0.588$). The ANOVA test met the homogeneity of variances condition (Levene = 2.114, $p = 0.078$).

Although the design is reproducible, reliable, and accessible, it requires 3D printing. This technology is not universally available, but it is expected to become increasingly common in educational settings, thus increasing universal access to the experimentation that this design entails.

The technical characteristics of components can vary between brands and models. For example, an electromagnet might exhibit lower hysteresis, or the rubber chosen to protect the piezoelectric element might be more rigid. Therefore, it is recommended to repeat the calibration when building devices or replacing components. Regular battery charging is also advised.

Finally, the students who took measurements were trained to perform high-precision measurements. In real educational settings, the variations could be more significant.

Conclusions

The device for measuring local gravity is an accurate, reliable, and affordable educational tool. Evaluation revealed that the five devices offer high consistency and accuracy, with a coefficient of determination of 1.00 and variations of less than 0.42%, surpassing most of the literature. A statistical ANOVA analysis supports the Repeatability and Reproducibility (R&R) of the devices, a novel approach not found in similar studies. The results reinforce the feasibility of using the device at upper secondary and higher education levels.

Compared to other studies, this project stands out for its precision and scale of measurements. Five devices were built, and hundreds of measurements were taken by five operators, maintaining remarkable consistency. This level of comprehensive testing was not found in previous studies, giving this research significant value.

The project represents an effective and accessible alternative for teaching physics. Its cost is considerably lower than that of commercial devices, making it a solution that can be replicated by other institutions. Releasing the files as open source promotes scientific transparency and contributes to Sustainable Development Goal 4, fostering equitable, quality education. This allows students in schools with limited resources to build high-quality devices at a lower cost, breaking down socioeconomic barriers to accessing scientific knowledge.

Limitations and future lines of research

The main limitation is technical and relates to reproducibility. Component heterogeneity can affect the model. Two examples are the circuit board and the electromagnet. The hysteresis of the electromagnet and the weight of the ball bearing will determine the fall delay. Processing speed also has an effect; for example, the circuit board used was 12 MHz, while the original Arduino UNO is 16 MHz. Each reproduced device requires calibration. It's also worth mentioning that the released model includes a gap for a 3.7 V battery to power the electromagnet. Keeping it charged to at least 3.5 V is vital for achieving consistent measurements.

The other main limitation is pedagogical. The reported level of accuracy required extremely careful measurements. In school settings, the results may vary significantly.

The modular design fosters future research through expansion ports C and D, which allow for the incorporation of additional experiments. Future work will develop additional modules for other phenomena (projectile motion and uniformly accelerated rectilinear motion). Furthermore, the integration of a motorized system for handling predefined heights will be explored.

File availability

To promote educational equity in the experimental teaching of physics, the design files, source code, and assembly and operation instructions are available under a Creative Commons BY-NC-SA 4.0 license in the Zenodo repository (<https://doi.org/10.5281/zenodo.17369280>).

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References

- Bu Sinnah, Z. A. y Muhammed, S. (2022). Determination of free falling acceleration gravity by using simulations and practical methods. *Arab Journal for Scientific Publishing*, 6.
- Casaburo, F. (2021). Teaching physics by Arduino during COVID-19 pandemic: the free falling body experiment. *Physics Education*, 56(6).
<https://doi.org/10.48550/arXiv.2105.03888>
- Centro Nacional de Metrología. (2016, 22 de febrero). *Nuevo patrón de gravimetría en el CENAM*. Gobierno de México. <https://www.gob.mx/cenam/prensa/nuevo-patron-de-gravimetria-en-el-cenam?idiom=es>
- Coluci, V. R., Paulino, G., Souza, D. C. d. y Vasconcelos, E. P. (2013). Ilustração de incertezas em medidas utilizando experimentos de queda livre. *Revista Brasileira de Ensino de Física*, 35. <https://doi.org/10.1590/S1806-11172013000200026>
- Di Bella-Nava, P., Segarra-Alberú, M. y Velázquez-Aguilar, V. M. (2019). Using experimental modules to favour meaningful learning in high school physics. *Journal of Physics: Conference Series*, 1287(1), 012012. <https://doi.org/10.1088/1742-6596/1287/1/012012>
- El Hadi, M., El Moussaouy, A., Ouariach, A., Essaadaoui, R., Hachmi, A., Laabidi, K., Magrez, H. y Meziani, Y. (2020). Real time free fall investigation for educational purposes using Arduino Uno board. *Physics Education*, 55(5).
<https://doi.org/10.1088/1361-6552/aba12f>
- García-Cruz, W. (2016). *Diseño y construcción de un instrumento para el estudio de la caída de los cuerpos: medicion de la aceleracion de la gravedad, por medio de Arduino* [Licenciatura en Física, Universidad Pedagógica Nacional]. Repositorio Institucional UPN. <http://hdl.handle.net/20.500.12209/2057>
- Harnsoongnoen, S., Srisai, S., Kongkeaw, P. y Rakdee, T. (2024). Improved Accuracy in Determining the Acceleration Due to Gravity in Free Fall Experiments Using Smartphones and Mechanical Switches. *Applied Sciences*, 14(6).
<https://doi.org/10.3390/app14062632>
- Hidalgo, M. y Medina, J. (2008). Introducción al cálculo de errores y tratamiento de datos. En *Laboratorio de física* (pp. 1-8). Pearson Prentice Hall.
- Horvat, D. y Jecmenica, R. (2016). The free fall experiment. *Resonance*, 21, 259-275.

- Instituto Nacional de Estadística y Geografía. (2021). *Aspectos geográficos. Zacatecas*.
https://www.inegi.org.mx/contenidos/app/areasgeograficas/resumen/resumen_32.pdf
- Juvinao Moyano, J. J. (2018). *Diseño e implementación de prácticas de laboratorio como estrategia de aprendizaje. Cinemática y dinámica para el área de física de grado décimo* [Tesis de maestría, Universidad Nacional de Colombia]. Repositorio Institucional UNAL. <https://repositorio.unal.edu.co/items/f85cfd98-d641-464a-a388-6637a2783219>
- Marte, S. J., Bug-os, M. A. A. C. y Pili, U. B. (2024). Comparative experiment using free fall and projectile motions in determining the acceleration due to gravitational force. *Physics Education*, 59(4). <https://doi.org/10.1088/1361-6552/ad4f40>
- Martín-Ramos, P., Silva, M. R. y da Silva, P. S. P. (2017). Smartphones in the teaching of Physics Laws: Projectile motion. *Revista Iberoamericana de Educación a Distancia*, 20(2). <https://doi.org/10.5944/ried.20.2.17663>
- Moya-Molina, A. Á. (2020). Un experimento basado en Arduino para estudiar el movimiento de caída libre en el aula. *Revista Española de Física*, 34(1), 33-35.
- Mukhopadhyay, B., Srirangarajan, S. y Kar, S. (2018). Modeling the analog response of passive infrared sensor. *Sensors and Actuators A: Physical*, 279. <https://doi.org/10.1016/j.sna.2018.05.002>
- Organización de las Naciones Unidas (2025). Objetivos de desarrollo sostenible: 4 educación de calidad. <https://www.un.org/sustainabledevelopment/es/education/>
- Provasi, P. F., Bogado, S., Pedrini, D., Merino, C. y Bentz, E. (2021). Diseño dispositivo pedagógico para demostración y aplicación del MRUA empleando Arduino. *Revista Conexiones*, 1(7), 74-80. <https://ojs.ucp.edu.ar/index.php/conexiones/article/view/894>
- Serway, R. A. y Jewett, J. W. (2018). *Física para Científicos e Ingenieros (Vol. 1)*. Cengage Learning.
- Shi, X., Wang, X., Zhang, L. y Guo, K. (2021). Influence factors of gravitational acceleration near the earth. *Journal of Physics: Conference Series*, 1865(2). <https://doi.org/10.1088/1742-6596/1865/2/022014>
- Shigley, J. (1993). *Teoría de máquinas y mecanismos*. McGraw-Hill.

- Solis, D. H., Hutchinson, D. y Longnecker, N. (2021). Formal Learning in Informal Settings—Increased Physics Content Knowledge After a Science Centre Visit. *Frontiers in Education*, 6(322). <https://doi.org/10.3389/educ.2021.698691>
- Song, E. Z., Zhao, G. F., Yao, C., Ma, Z. K., Ding, S. L. y Ma, X.-Z. (2018). Study of nonlinear characteristics and model based control for proportional electromagnet. *Mathematical Problems in Engineering*, 2018(1). <https://doi.org/10.1155/2018/2549456>
- Taylor, J. R. (1997). *An introduction to error analysis: The study of uncertainties in physical measurements*. University Science Books.
- Torres, C. (2023). *Diseño y construcción de un equipo para laboratorio de física de movimiento de caída libre operado mediante software*. [Tesis de Ingeniería, Universidad Tecnológica de Pereira]. Repositorio Institucional UTP. <https://repositorio.utp.edu.co/server/api/core/bitstreams/df7a6684-9cab-4877-9ba9-24da31591c7a/content>
- Vogt, P. y Kuhn, J. (2012). Analyzing free fall with a smartphone acceleration sensor. *The Physics Teacher*, 50(3), 182-183. <https://doi.org/10.1119/1.3685123>
- Walpole, R., Myers, R., Myers, S. y Ye, K. (2012). *Probabilidad y estadística para ingeniería y ciencias*. Pearson.

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