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Design and Development of an Automation Device for Free-Fall Motion Experiments Based on a Web-Remote Laboratory

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Abstract

Design and Development of an Automation Device for Free-Fall Motion Experiments Based on a Web-Remote Laboratory. *This study aims to develop an automated free-fall experiment device integrated with a web-remote laboratory system. The web-remote laboratory is a real laboratory that can be controlled and displays results remotely through an internet connection. The research follows the Design and Development Research (DDR) methodology, which encompasses several stages: problem identification, objective formulation, system design and development, system testing, evaluation, and refinement. A domain hosting service was employed to deploy the web server, providing greater flexibility and ease in developing control interfaces compared to applications such as Blynk and ThingSpeak. The design and development process addressed both hardware-mechatronic and software components. The software was implemented on the microcontroller and the webserver to enable seamless integration. Testing was conducted in two phases, which informed product evaluation and subsequent refinements. The resulting device supports automation, features fully functional mechatronic systems, ensures optimized sensor sensitivity, facilitates user-friendly control via a web browser, and provides accurate calculations of gravitational acceleration during free-fall experiments. Despite its strengths, the ESP8266 microcontroller was suboptimal for applications requiring high sensitivity. Additionally, the web interface lacked multi-user support. These limitations present opportunities for further development and optimization of the device. Overall, the findings of this study provide a practical and innovative solution to enhance student engagement in laboratory activities, particularly in educational settings with limited access to physical laboratory equipment.*

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INTRODUCTION

Physics education emphasizes the inclusion of laboratory-based practical activities. These activities are essential for developing students' scientific process skills, reasoning abilities, and scientific thinking. A preliminary study in March 2022 involving 48 prospective physics teachers in Central Kalimantan revealed that most respondents experienced limited practical physics activities during high school, with the majority conducting experiments less than three times or never, and only 25% conducting them more than three times. This finding highlights a key issue: limited tools and resources in schools hinder the effective implementation of practical activities. Innovative solutions are needed to enable students to engage in laboratory activities even in the absence of traditional laboratory equipment.

One proposed solution is the use of remote laboratories (Arguedas-Matarrita et al., 2019; Asrizal et al., 2024; Laouina et al., 2023; Lerro et al., 2012; Matarrita & Beatriz Concari, 2016; Mebiyantara et al., 2021; Urbano et al., 2023; Žovínová & Ožvoldová, 2011). Remote laboratories operate similarly to virtual laboratories in principle (Aprilianti et al., 2024; Fadli et al., 2022; Hizbi, 2019; Hizbi & Fartina, 2018; Makhrus et al., 2020; Nurhasanah et al., 2023; Susilawati et al., 2020), with the key difference being the use of real instruments in remote laboratories compared to virtual instruments implemented through application programs in virtual laboratories (Alkhaldi et al., 2016; Fabregas et al., 2017; Hizbi, 2019). This innovation is expected to address limitations in laboratory tools and prevent equipment damage during practical activities (Tukan & Julian, 2017).

This study leverages advancements in IoT and web-based learning to design and develop remote laboratory instruments, providing an innovative approach to enhancing physics education. Several studies have developed simple, easy-to-construct, and low-cost IoT devices (Annovasho et al., 2017, 2021). Examples of IoT applications in physics practical activities include using the Phyphox app (Boimau et al., 2021), Newton's second law teaching aids utilizing ThingSpeak (Muchlis et al., 2018), free-fall motion experiment tools using Blynk (Agustian et al., 2024), microcontrollers with PC displays (Dasriyani et al., 2015), and uniformly accelerated motion (UAM) experiment devices employing infrared sensors (Rudianto et al., 2024).

Web-based and application-based learning media have also been developed, such as interactive Android-based media (Ihsan et al., 2024) and web-based learning for Light topics (Pajrianor et al., 2024). The application of remote laboratories aligns with STEAM education and active learning media, which positively impact students (Witdiya et al., 2023; Yuliani et al., 2024). Additionally, integrating remote laboratory instruments into STEAM-PjBL approaches enhances students' soft skills and metacognitive awareness (Nasir et al., 2024). The study has yet to establish a connection between web-based learning, STEAM education, or active learning media with the use of real laboratory equipment.

Research on remote laboratories remains insufficiently developed in developing countries. Although some researchers have attempted to implement this concept, further development of physics experimental instruments has been limited. This study seeks to explore and advance the application of remote laboratories, aiming to address these gaps and contribute to the progression of this field. Advancements in ICT and increased internet accessibility facilitate the implementation of remote laboratories, enabling students to conduct experiments online with real-time feedback, and offering flexible, accessible, and interactive learning experiences that overcome the constraints of physical laboratories. The proposed automation concept ensures that the device operates entirely without physical intervention from users, technicians, or laboratory staff. All instrument-related operations, including results and calculations, are managed and displayed via the web interface. The development of a web-remote laboratory introduces a new dimension, differing from previous studies that predominantly used existing applications such as Blynk or ThingSpeak (Agustian et al., 2024; Muchlis et al., 2018). The use of web-based solutions provides unparalleled flexibility in full customization, seamless integration capabilities, and direct control over infrastructure and data, eliminating reliance on third-party platforms. This research on remote laboratories contributes to the achievement of the Sustainable Development Goals (SDGs) (Georgakopoulos et al., 2023; Poo et al., 2023), particularly Goal 4 (Quality Education), by enhancing access to quality science education through innovative, scalable, and inclusive learning platforms that overcome geographical and resource limitations.

METHODS

The research employed a design and development research (DDR) approach. Unlike research and development (R&D), which tends to focus more on the creation of new products or innovations and is limited to results that can be quantitatively measured, Design and Development Research (DDR) places greater emphasis on understanding the processes involved in applying practical solutions and testing theories within more dynamic and contextual settings. This allows researchers to continuously evaluate and refine designs based on direct feedback, which is crucial for developing solutions that are not only effective but also relevant and aligned with the needs of the users. DDR is the most appropriate approach for research objectives that require the integration of theory and practice, as well as the flexibility to adapt designs and solutions within complex and ever-evolving real-world contexts. This approach enables researchers to conduct iterative testing, reflect on findings, and implement more effective and sustainable solutions.

DDR encompasses a series of stages, including the design, development, and evaluation of a product or tool. In this study, the product developed was an automated free-fall motion experiment device based on a web-remote laboratory system. This product is the first device to integrate a web system for free-fall experiments, enabling real-time monitoring, control, and data analysis while addressing common challenges faced by teachers and students in conducting experiments that require equipment and conditions typically found in a real laboratory setting. This study focuses solely on the performance of the tool, without delving further into its implementation or the interactions between the tool, teachers, or students.

The design and manufacturing process of the product was carried out at the Physics Instrumentation Workshop of IAIN Palangka Raya. The facility is equipped with advanced workshop tools, stable internet connectivity for testing, and strict safety procedures. Specifically, DDR in this study was divided into six phases: problem identification, objective determination, system design and development, system testing, evaluation of testing, and product refinement. Problem identification dan objective determination consist of the preliminary study process and literature review, system design and development consists of hardware/mechatronic design and software development, system testing includes limited testing and real-world situational testing, and evaluation of testing is the phase for reviewing notes from the testing stage and planning improvements, product refinement is the phase for making improvements based on the evaluation that has been compiled. (Asrizal et al., 2024).

The tools and materials used included wooden and iron frames, a power supply, an ESP8266 microcontroller, infrared sensors, DC motors, a solenoid magnet, a threaded shaft, iron rails, and an acrylic/PMMA tube. The ESP8266 microcontroller was selected due to its affordability and comprehensive functionality. For the web interface, a domain-hosted web server was utilized, accessible via the URL www.belajar-fisika.org. The web hosting server used demonstrates high reliability and sufficient stability to support learning scenarios involving multiple users simultaneously, while providing easy access for users, with relatively low maintenance costs compared to other server solutions.

The calculations for free-fall motion are described as follows. The acceleration experienced by any freely falling object is constant and equivalent to the gravitational acceleration of the Earth. Free-fall motion adheres to the laws of uniformly accelerated linear motion (UALM), as expressed in Equation (1):

$$x - x_0 = vt - \frac{1}{2}at^2 \quad (1)$$

In the case of free-fall motion, the initial velocity v=0, and x-x_0 represents the free-fall height, denoted as h. The vertical acceleration (a) is equivalent to the gravitational acceleration

(g) during free-fall motion. The equation for free-fall time shows that the duration of free fall depends only on two factors: h (height) and g (gravitational acceleration). Therefore, the weight of the object does not influence the free-fall time. This indicates that two objects with different masses, dropped from the same height in the same location, will fall in the same amount of time. Figure 1 illustrates the trajectory of free-fall motion.

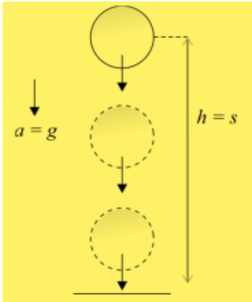


Figure 1. Illustration of free-fall motion trajectory

Based on the above description, the relationship between h and g is given by Equation (2):

$$h = -\frac{1}{2}gt^2 \quad (2)$$

If h (height) and t (time) are known, the gravitational acceleration can be calculated using Equation (3):

$$g = \frac{2h}{t^2} \quad (3)$$

(Giancoli, 2015)

The calculation in Equation (3) was implemented in the program to determine gravitational acceleration. The implementation of the calculation in Equation (3) within the program to determine gravitational acceleration directly enhances the practical understanding of physics theories by providing a hands-on approach to applying theoretical concepts in real-time experiments. This integration not only reinforces the connection between theoretical knowledge and practical application but also improves the device functionality by enabling accurate, real-time measurements, thereby allowing users to better observe and analyze gravitational effects in different experimental setups.

RESULTS AND DISCUSSION

Phase of Problem Identification and Objective Determination

The device must be able to measure the time it takes for a 100-gram iron ball to fall from a certain height. The iron ball should fall freely, meaning without any external forces or the influence of air anomalies. When the ball begins to fall, the time calculation starts and ends when the ball has traveled a distance of 100 cm, which is when it is detected by the second sensor. The use of a 100-gram iron ball and a 100-cm track length is necessary to simplify the calculations. The time data obtained will be processed by the system and displayed on the practitioner's web browser. The gravitational acceleration calculation results from the remote laboratory device are compared with the calculations obtained using the free-fall apparatus through manual methods. The ball is then placed in the collection carrier and returned to the top position via a command given through the web server. The problem identification and objective determination phase is illustrated in the flowchart shown in Figure 2.

Design

Hardware Design

The device utilizes the ESP8266 microcontroller as the central control unit. It is powered by a 5-volt power supply. The ESP8266 is capable of directly connecting to a Wi-Fi access point, eliminating the need for additional modules. The microcontroller is responsible for receiving input from the sensors and forwarding commands from the web server to the actuators. The system employs two infrared sensors to measure the time it takes for the ball to fall a distance of 100 cm. The actuators include a DC motor and two solenoid magnets. The DC motor is responsible for rotating the threaded shaft, which raises the collection container to position the ball at the starting point (at the top of the path). One solenoid magnet is used to secure the ball at the starting position, ensuring the ball remains in a free-fall state, free from external forces, when the device begins timing. The second solenoid functions as a gate, allowing the ball to enter the collection container. The data flow diagram of the designed system is illustrated in Figure 3, and the device design is presented in Figure 4.

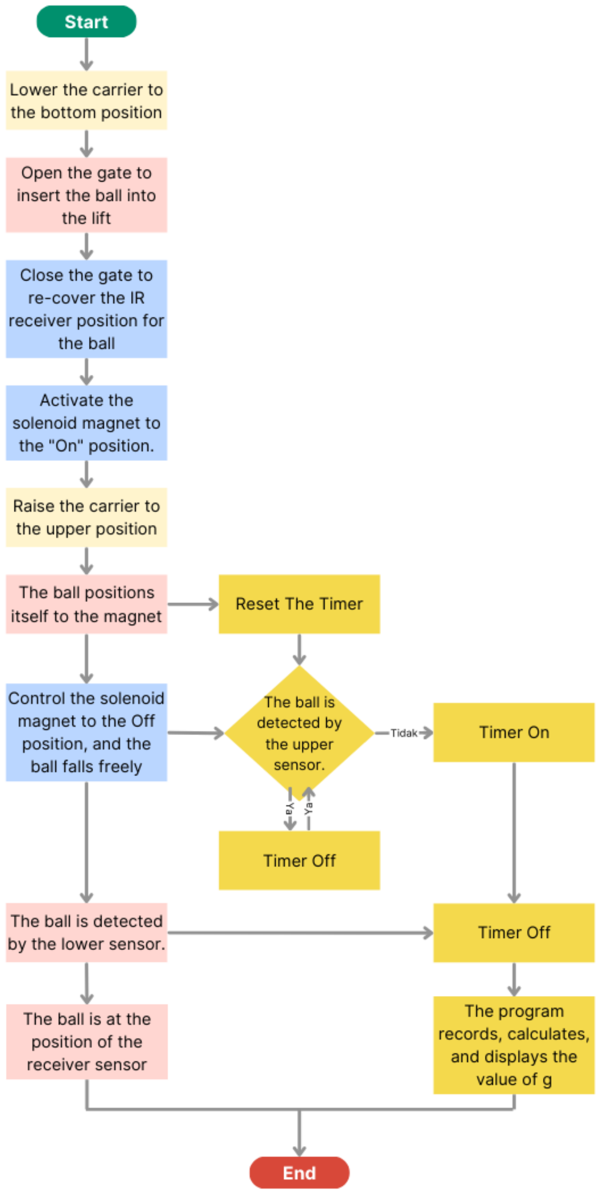


Figure 2. Flowchart of the Web-Remote Laboratory

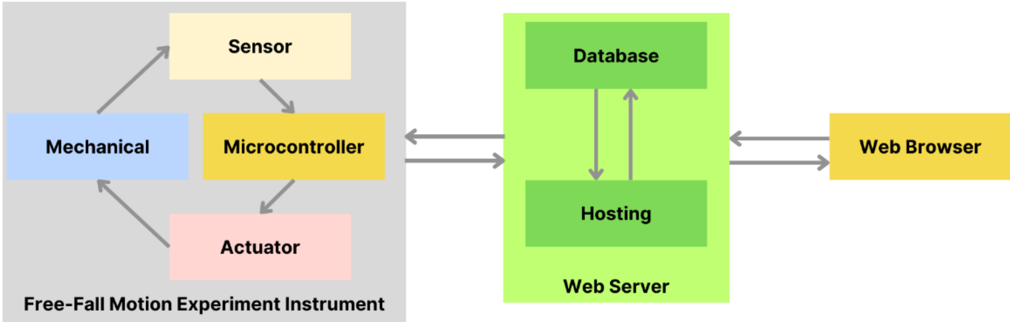


Figure 3. Data Flow Diagram of the Web-Remote Laboratory Design

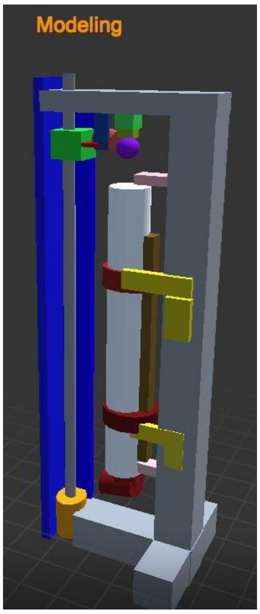


Figure 4. Mechatronic Design of the Web-Remote Laboratory

The measurement of free-fall motion is conducted using a 100-gram iron ball. To ensure accurate calculations, the free-fall path is set at a height of 100 cm. To eliminate the influence of air anomalies along the fall path, a 100 cm long acrylic/PMMA tube is utilized, as shown in Figure 4.

Software Design

The software designed for the system consists of two main components: a set of commands programmed to operate the microcontroller and commands designed to manage the web server. These two components are interconnected via a database, which is part of the web hosting infrastructure. The communication protocol used is HTTPS. Network security is provided by the hosting service provider in the event of any attacks during the process.

The microcontroller software includes instructions to process inputs from sensors and transmit the data to the web server, as well as commands to receive instructions from the web server and relay them to the actuators. The actuators in this system comprise a DC motor and a ball gate mechanism.

The web server software, in contrast, facilitates communication between the web client and the microcontroller. Its responsibilities include forwarding commands from the web client to the microcontroller and displaying and processing data from the microcontroller for the web client.

The microcontroller was programmed using the Arduino IDE application, with code written in the C# programming language. To ensure reliability, the software underwent a thorough validation process. This included unit testing, where individual components of the code were tested in isolation to verify their functionality. Additionally, system testing was conducted to evaluate the integration of the software with the hardware, ensuring that all components interacted correctly. Debugging was performed to identify and resolve any errors or issues within the code, ensuring the program operated as intended. These testing procedures were critical to validate both the software and hardware, ensuring the system's stability and accuracy in real-world applications. The web server program, meanwhile, was developed using a text editor on the hosting server, with scripts written in PHP and HTML.

Development

Hardware Development

The device was meticulously developed based on the concepts established during the problem identification, objective determination, and design phases. The finalized device, depicted in Figure 5, comprises multiple components, each performing specific functions as defined in the design phase.

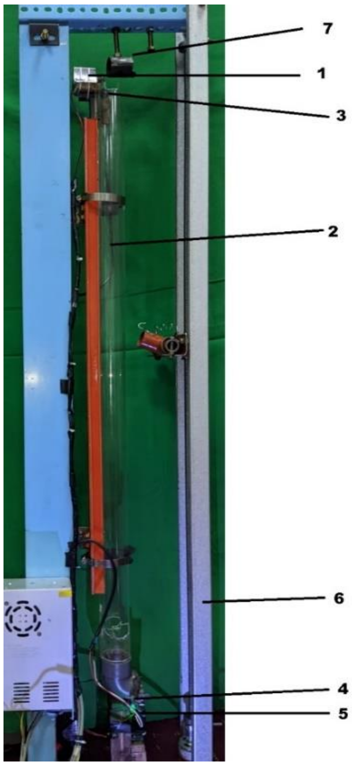


Figure 5. Web-Remote Laboratory Device

In Figure 5, the description of each component is as follows:

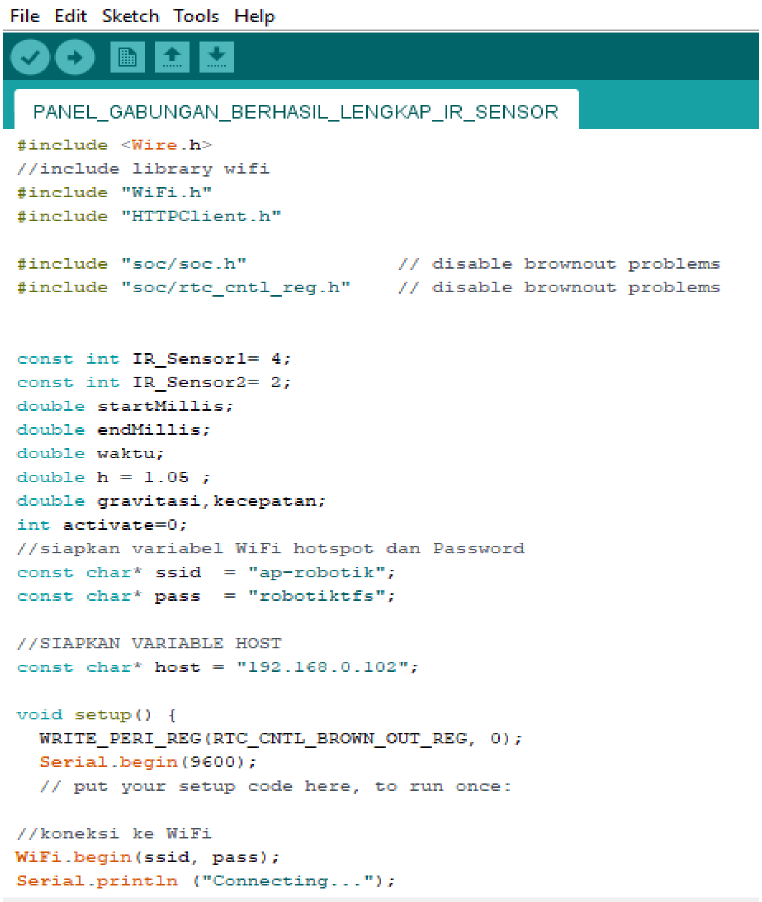
1. Ball-holding solenoid Magnet
2. Free-Fall Track Tube
3. Upper IR Sensor
4. Ball Drop Pipe
5. Ball Gate Solenoid
6. Ball Carrier Slider

7. Ball Positioning Pipe
8. Power Supply
9. Ball Carrier Slider Holder

Software Development

1. Software in the ESP8266 Microcontroller

The software was created using the Arduino IDE program and uploaded to the device. The Arduino IDE interface is shown in Figure 6.




```
#include <Wire.h>
//include library wifi
#include "WiFi.h"
#include "HTTPClient.h"

#include "soc/soc.h"             // disable brownout problems
#include "soc/rtc_cntl_reg.h"    // disable brownout problems


const int IR_Sensor1= 4;
const int IR_Sensor2= 2;
double startMillis;
double endMillis;
double waktu;
double h = 1.05 ;
double gravitasi,kecepatan;
int activate=0;
//siapkan variabel WiFi hotspot dan Password
const char* ssid  = "ap-robotik";
const char* pass  = "robotiktfs";

//SIAPKAN VARIABLE HOST
const char* host = "192.168.0.102";

void setup() {
  WRITE_PERI_REG(RTC_CNTL_BROWN_OUT_REG, 0);
  Serial.begin(9600);
  // put your setup code here, to run once:

//koneksi ke WiFi
WiFi.begin(ssid, pass);
Serial.println ("Connecting...");
```

Figure 6. Code in the Arduino IDE

2. Software on the Hosting Server

The software provided on the web server is designed to manage inputs from the practitioner through the web browser and forward them to the controller. Additionally, it receives results from the controller and displays them on the web browser. The code for the web server is written in PHP and HTML. The following types of code are used for database configuration and the user interface: 1) controlling the relay, 2) ensuring connectivity with the device, 3) sending data, 4) creating the main page display (Index), 5) controlling the gate, 6) controlling the DC motor's clockwise (CW) rotation, 7) checking time, 8) checking speed, 9) checking gravitational acceleration, 10) controlling the DC motor's counterclockwise (CCW) rotation, 11) reading the relay position, 12) reading the gate position, and 13) reading the direction of DC motor rotation (CW-CCW). An example of the code, shown in Figure 7, illustrates the configuration for the main page display written in HTML.

```
<!--baca status trakhir relay dan servo--->
<?php
include "koneksi.php";

$sql = mysqli_query($konek, "SELECT * FROM tb_panel");
$data = mysqli_fetch_array($sql);
//ambil status relay
$relay = isset ($data ['relay']) ? $data ['relay']:'';
$cw = isset ($data ['cw']) ?  $data ['cw']:'';
$ccw = isset ($data ['ccw']) ?  $data ['ccw']:'';
$servo = isset ($data ['servo']) ?  $data ['servo']:'';
 ?>


  <!doctype html>
<html lang="en">
  <head>
       <div class="container" style="text-align:center; padding-top: 11px;">
     <h2> <br> </h2>
    </div>
     <!-- Required meta tags -->
     <meta charset="utf-8">
     <meta name="viewport" content="width=device-width, initial-scale=1, shrink-to-fit=no">

     <!-- Bootstrap CSS -->
     <link rel="stylesheet" href="https://maxcdn.bootstrapcdn.com/bootstrap/4.0.0/css/bootstrap.min.css"
     integrity="sha384-Gn5384xqQ1aoWXA+058RXPxPg6fy4IWvTNh0E263XmFcJlSAwiGgFAW/dAiS6JXm" crossorigin=
     "anonymous">


     <script type="text/javascript" src="jquery/jquery.min.js"></script>
     <!-- load otomatis/realtime -->
     <script type="text/javascript">

       $(document).ready( function() {

         setInterval( function() {
           $("#cekgravitasi").load("cekgravitasi.php");
           $("#cekkecepatan").load("cekkecepatan.php");
           $("#cekwaktu").load("cekwaktu.php");
         }, 1000 );

       } );
     </script>


   </head>
```

Figure 7. Main page code in HTML

The main page on the web browser appears as shown in Figure 8 below.

Figure 8. Main page display of the web-remote laboratory.

The description for each section in Figure 8 is as follows:

1. Monitoring the time taken by the iron ball
2. Monitoring the speed of the ball at the receiver sensor
3. Monitoring the calculation of gravitational acceleration
4. Solenoid Magnet Control
5. Control for raising the ball collection rail
6. Control for lowering the ball collection rail
7. Control for the solenoid gate.

The procedure for utilizing the remote laboratory experiment device is as follows:

1. Ensure that the Free Fall Motion remote laboratory device is properly positioned and ready for use.
2. Access the website at http://belajar-fisika.org/.
3. Verify that the site is accessible and properly connected to the device.
4. Locate the position of the iron ball by observing the video feed on the monitor. If the iron ball is not visible, position the collection container at the lower end by pressing the DOWN button to switch to RUN mode, continuing until it stops at the bottom. Then, press the DOWN button again to return to STOP mode.
5. Press the GATE button to switch to OPEN mode, and then press it again to return to CLOSE mode.
6. Activate the Solenoid Magnet by pressing the MAGNET button to the HOLD mode. This ensures the iron ball remains in position at the top of the device until the timing commences.
7. Raise the collection container to the top position by pressing the UP button to switch to RUN mode. Once at the top, press the UP button again to switch to STOP mode.
8. Release the iron ball from the solenoid magnet by pressing the MAGNET button to the GO mode. This action will release the ball, allowing it to fall freely.
9. The sensor will record the time taken for the ball to travel. Time, speed, and gravitational acceleration will be displayed in the monitoring section. Record the results in your worksheet.
10. Repeat steps 4 to 9 a total of five times to ensure the accuracy of the results

System Testing

The testing process was conducted in two phases. The first phase took place in the physics laboratory at IAIN Palangka Raya, while the second phase was carried out in schools with students serving as practitioners. During the first phase, any challenges encountered were recorded and immediately addressed to ensure alignment with the original design and development framework. Any deviations were promptly rectified.

The second phase of testing was performed at three partner schools: MA Darul Falah in Pulang Pisau Regency, MA Negeri Kapuas in Kapuas Regency, and MA Darul Ulum in Palangka Raya City. The documentation of this second-phase testing process is presented in Figure 9. The primary focus of the second phase was to assess the practicality of the device's usage. Based on the user manual, six active steps were identified: steps 2, 4, 5, 6, 7, and 8. These steps were critically evaluated to determine their necessity and feasibility in real-world applications. Additionally, the effectiveness of the device was assessed, and any challenges encountered during its use were thoroughly examined.

Figure 9. Web-Remote Laboratory Device Testing

Evaluation of Testing

During the implementation/testing phase, several challenges were encountered. Initially, the device operated smoothly when first turned on. However, with groups of 6 to 8 students per school, issues began to arise midway through the experiment. The following are the challenges or problems faced during the practical sessions using the remote laboratory device:

1. Network Disconnection.

   In all three schools, the network used was 4G data from the researcher's smartphone. This decision was made for the sake of convenience, as setting up a dedicated access point would have taken longer than using the available school networks. However, this decision resulted in disruptions during the practical sessions. On several occasions, the network disconnected, leading to slow device response, inaccurate calculation results, and devices continuing to operate despite receiving stop commands. The device could only function properly once the network connection was restored.
2. Failure of the Solenoid to Capture The Ball.

   During the trial, there were instances where the solenoid failed to capture the ball, preventing it from remaining in the starting position. This occurred because the trajectory of the ball did not align with the designated capture position. Over time, the alignment of the path shifted slightly, causing the ball's trajectory to deviate. As a temporary solution, tape was applied to guide the ball along the correct path.

3. Ball Not Detected by the Photodiode Sensor.

   This issue was related to the previous one, where the ball did not follow the correct path and consequently was not detected by the photodiode sensor. The same temporary solution was applied: tape was used to guide the ball along the correct path. Once the path was properly aligned, the ball would occupy the correct position and be detected by the photodiode sensor.

4. Slow Response of the Photodiode in Performing Calculations.

   At the final sensor position, the photodiode often failed to detect the ball's movement, and when it did, the response time was slow. This was the primary issue encountered during the use of the device. Several alternatives were attempted before validation, including using two separate microcontrollers, where one ESP8266 was dedicated to capturing sensor data and the other to control actuators/movement mechanisms. Unfortunately, this did not resolve the issue. Nonetheless, data was still collected under the existing conditions. A temporary solution involved fixing the position of the ball's fall to provide a stable reference point for the sensor to perform accurate readings. The updated ESP8266 configuration scheme is shown in Figure 10.

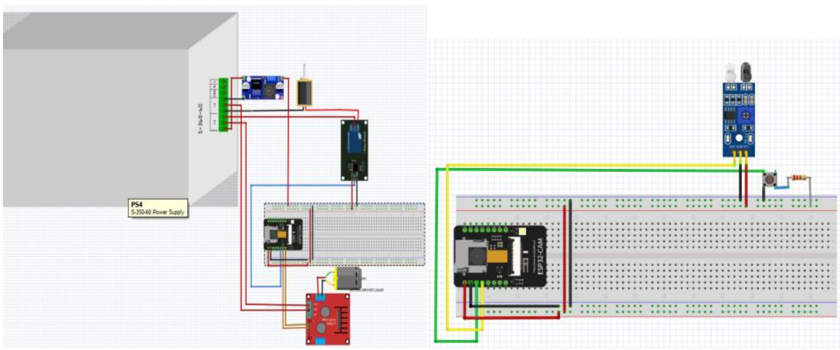


Figure 10. Remote laboratory system equipped with two microcontrollers

5. Ball Fails to Enter the Carrier Bin

   The next issue encountered is the failure of the ball to enter the carrier bin once it reaches the final position. Similar to the previous issue, the imprecision in the ball's position results in it not being pushed fully into the carrier bin. The lack of precision in the ball's position occurs due to a shift between the positions of the carrier bin and the final position of the ball when the solenoid gate is activated. As a result, the ball remains in its position instead of being pushed into the carrier bin. This causes a delay in the experiment, requiring manual intervention by the operator to relocate the ball into the bin.

6. Ball Ejected from the Carrier Bin

   Once the ball is inside the carrier bin, an unstable holder causes the ball's position to shift. At a certain point, the ball is ejected from the bin, causing it to fall to the floor. Manual intervention is required to retrieve the ball from the floor and place it back into the bin. Although this issue does not occur consistently, it is relatively frequent in certain circumstances.

7. Failure in DC Motor and Motor Driver Function

   The DC motor used as a driver has experienced several failures. The first issue arises when the control command for upward or downward movement is issued, but the motor's response is delayed. The second issue occurs when the motor should stop but fails to do so promptly, causing both the motor driver and the DC motor to overheat. When the system overheats, a cooling period is necessary, as overheated components respond more slowly to commands. This second issue is related to the first and may also be caused by network-related disruptions.

Product Refinement

Based on the evaluation of the experimental device conducted, the primary issue lies in the mechatronic process involving the load ball. The solutions to these issues are as follows:

1. Network Disconnection
   Placing the device within a stable network is a key objective of this development. During testing, the conditions were not ideal for experimenting. Therefore, using a network under ideal conditions, where only one device is connected to the internet at a single location, differs significantly from the experimental situation, where each access point bears the network load for two or more devices.
2. Ball Fails to Stick to the Solenoid
   Improvements and further evaluation are required to address this issue. The solution involves adjusting the optimal distance between the container on the lifting rail, the ball's path, and the solenoid's position, ensuring tolerance in the distance. This adjustment ensures that, during multiple trials, the ball is precisely caught by the solenoid at the starting position.
3. Ball Not Detected by Photodiode Sensor
   This issue is related to the sensor's sensitivity, a common problem (Muchlis et al., 2018; Rudianto et al., 2024). The slow response of the photodiode in making calculations has led to the decision to replace the final position sensor with a switch. A switch offers more reliable reading certainty because the ball, when falling freely, has high velocity. The small size of the ball also makes it difficult for the sensor to detect its movement, unlike a switch that directly toggles between on/off states when impacted by the falling ball.
4. The Ball Does Not Enter the Carrier Bin
   Recalibration of the ball's position is needed to ensure it enters the bin on the lifting rail. Calibration can be achieved by adding protective foam to guarantee that the ball’s trajectory aligns precisely with the bin's position on the lifting rail.
5. The Ball Ejected from the Carrier Bin While Moving Up
   The solution to this issue is to replace the carrier bin's rail structure with a more rigid one that offers better stability. The structure will consist of welded iron frames, precisely calibrated to prevent the bin from shaking. This will ensure that the ball remains stable while inside the bin on the lifting rail.
6. DC Motor and Motor Driver Malfunction
   Ensuring that the network used is stable and that the devices are not overheating is critical for maintaining the performance of the DC motor and motor driver. Additionally, heat sinks can be added to the device box or near the motor driver to maintain temperature control, ensuring that the DC motor performs optimally.
   Based on these six improvements, further modifications to the device are outlined in Table 1 below.

Table 1. Product Refinements

No. Improvements	Before	After
1	One access point is used for multiple devices.	One access point is used for a single device.
2	 The release distance from the carrier bin is too short, and the ball's path is too steep. The IR sensor/photodiode lacks sensitivity.	 Adjust the distance and slope of the ball's path from the carrier bin to the solenoid magnet. Use a more sensitive IR sensor/photodiode.
3	 Use an IR sensor/photodiode as a time measurement stopper for free fall.	 Use a switch as a time measurement stopper for free fall.
4	 Use a tube and solenoid gate to hold the ball before it enters the carrier bin.	 Use a ball path mechanism so that once the switch is turned off, the ball will directly enter the carrier bin.
5	 The carrier bin rail is made of lightweight steel, which is insufficiently rigid and causes	 The carrier bin rail uses solid steel, which is more rigid,

No. Improvements	Before	After
6	vibrations when the bin lifts the ball upward.  An integrated control box has not yet been used to secure the device's temperature.	significantly reducing vibrations when carrying the metal ball.  An integrated control box has been used to secure the device's temperature.

The final appearance of the free fall motion experiment automation device, based on the web-remote laboratory, is shown in Figure 11.

Figure 11. The web-remote laboratory-based free fall motion experiment automation device after the improvements.

Given the modification of the device's functionality based on test data from the school, it is essential to adjust the workflow in Figure 2 to reflect the changes depicted in Figure 12.

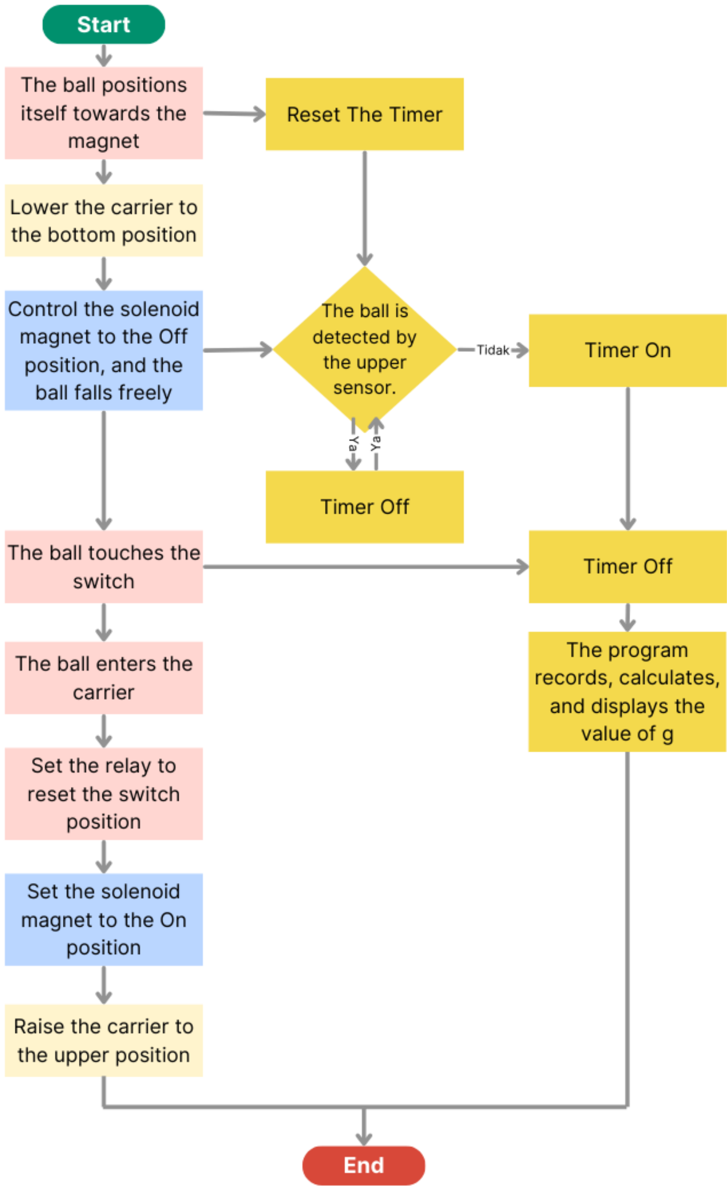


Figure 12. Adjusted Web-Remote Laboratory Flowchart

As outlined in Figure 12, the procedural steps for operating the remote laboratory experiment device have been thoroughly evaluated and are as follows:

1. Ensure that the remote laboratory Free Fall Motion device is properly positioned and prepared for use.
2. Access the following web address: http://belajar-fisika.org/.
3. Confirm that the website is accessible and that the device is successfully connected.
4. Verify that the metal ball is correctly positioned within the solenoid magnet.
5. Position the carrier bin at the lower end by pressing the DOWN button to initiate RUN mode, allowing it to move to the bottom. Once the bin has stopped, press the DOWN button again to switch to STOP mode.
6. Release the metal ball from the solenoid magnet by pressing the MAGNET button to engage GO mode. This will release the ball and allow it to fall freely.

7. The falling metal ball will activate the switch. The controller will record the time from the initial sensor activation to the switch event. Time, velocity, and gravitational acceleration data will be displayed in the monitoring section. Ensure that these results are recorded in the worksheet.
8. The ball will automatically enter the carrier bin. Adjust the servo to a 90-degree position to reset the switch and return it to the 0-degree position.
9. Activate the solenoid magnet by pressing the MAGNET button to engage HOLD mode. This will secure the metal ball in place until the measurement process begins.
10. Elevate the carrier bin to the top position by pressing the UP button to initiate RUN mode. Once the bin reaches the top, press the UP button again to switch to STOP mode. The ball will roll and attach to the solenoid magnet.
11. Repeat steps 4 through 9 five times to ensure the accuracy and reliability of the results.

After adjusting the workflow, the web interface was also modified, as shown in Figure 8, and updated to Figure 13 below.

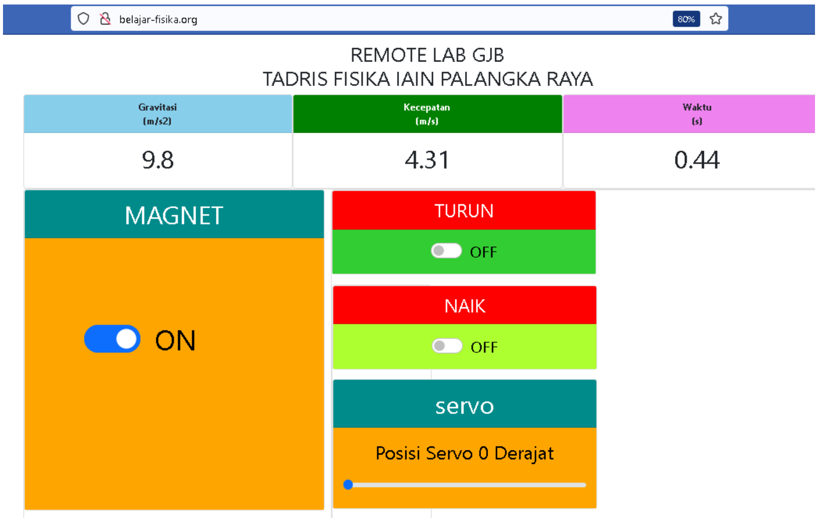


Figure 13. Updated Main Page Display of the Remote Laboratory

The adjustments made significantly enhanced the accuracy of free-fall motion calculations. A comparison of gravitational acceleration calculation results using conventional apparatus and the web-remote laboratory, both before and after the refinements, across twenty iterations, is presented in Table 2. During these iterations, no issues were observed, unlike those encountered before the enhancements. Although not yet fully optimized, the device now performs sufficiently well to achieve the intended objectives of remote laboratory applications. The consistent design and development process has been shown to effectively improve the accuracy of gravitational acceleration measurements. (Dasriyani et al., 2015).

Table 2. A comparison of gravitational acceleration calculation results

Conventional Apparatus	Web-Remote Laboratory	
	before the refinements	after the refinements
9,477±0,076 m/s^2	9,934±4,014 m/s^2	9,486±0,992 m/s^2

The challenges encountered with the IoT device have been minimized. While the ESP8266 offers convenience, competitive pricing, and versatile capabilities, it does have limitations in data processing, such as delays. These delays may also stem from improper program flow (sketch) writing (Agustian et al., 2024; Asri & Mulyati, 2019; Rudianto et al., 2024; Setiawan & Purnamasari, 2019). The ESP8266 microcontroller is not ideal for applications requiring high sensitivity, such as in free-fall motion experiments. A micro-computer, such as the Raspberry Pi, would provide better sensitivity, connectivity, and data processing capabilities. Another challenge, as previously mentioned, concerns internet speed and the availability of a stable connection. A remote laboratory requires a fast and reliable connection, which significantly impacts the quality of the experiment (Tukan & Julian, 2017).

In the web browser/client interface, the design and development offer simple, intuitive, and user-friendly controls. However, this preliminary study does not yet support multiple users, a feature that could be integrated with a login system (Mebiyantara et al., 2021; Sládek & Válek, 2011). Further implementation improvements are needed to enhance web-remote laboratory access, allowing for greater student engagement in laboratory exercises, even when physical laboratory equipment is unavailable at their schools.

CONCLUSION

The research phases based on the Design and Development Research (DDR) model have been completed. The developed device supports automation, fully functional mechatronic components, optimized sensor sensitivity, an easy-to-use and intuitive web-based control interface, and accurate data for calculating gravitational acceleration in free-fall motion experiments. However, the ESP8266 microcontroller is less than optimal for experimental devices requiring high sensitivity. To distribute the workload, two ESP8266 units were utilized, one for actuator control and the other for processing sensor data. Further development is needed using control devices with greater data processing capacity, such as the Raspberry Pi or similar alternatives. Additionally, the current web browser/client interface does not yet support simultaneous multi-user access. These findings provide a valuable foundation for the further development of web-based remote laboratory experimental devices in Indonesia, offering an effective solution to facilitate student engagement in laboratory activities even in the absence of physical laboratory equipment in educational institutions.

SUGGESTION

Further development of the web-remote laboratory-based automated free-fall experiment device remains a promising area for the future, with a focus on enhancing the reliability of the hardware, software, and overall user system.

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