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Development of an Internet of Things (IoT) Based Grating Diffraction Experimental Device with Real-Time Light Intensity Data Acquisition

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Abstract

This study aims to develop an Internet of Things (IoT)-based diffraction grating experimental apparatus and to examine its feasibility and performance in physics laboratory activities. The research employs the Research and Development (R&D) method with the ADDIE development model, which includes the stages of analysis, design, development, implementation, and evaluation. The experimental apparatus developed consists of a laser diode light source, a diffraction grating, an LDR light sensor, a stepper motor as an automatic scanning system, and a NodeMCU ESP8266 microcontroller that functions as an IoT-based control and data acquisition system. The validation of the apparatus was conducted by subject-matter experts and media experts using an assessment instrument based on a Likert scale. The validation results indicate that the experimental apparatus falls into the very feasible category for use in physics laboratory activities. The performance testing of the apparatus shows that the system is capable of detecting the distribution of light intensity and the positions of diffraction maxima consistently. The calculation of the wavelength based on experimental data produces values in the range of 647–652 nm, which are close to the theoretical value of the light source of 650 nm with a low level of relative error. In addition, the use of an IoT-based system allows the data acquisition process to be conducted automatically and visualized in real time, thereby improving the efficiency and objectivity of measurements. The results of this study indicate that the developed experimental apparatus has the potential to support the modernization of physics laboratories and improve the quality of digital data based laboratory learning.

Keywords: diffraction grating, Internet of Things, light sensor, microcontroller, data acquisition system, optical sensor, NodeMCU ESP8266, optics experiment.

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Introduction

The development of science and technology in the era of the Industrial Revolution 4.0 has driven digital transformation across various sectors, including science education. The integration of digital technology into the learning process has become an essential necessity to create learning experiences that are more effective, interactive, and relevant to the demands of modern scientific and technological developments [1]. In the context of physics education, the utilization of technology functions not only as a learning medium but also as a means to improve the quality of experimental activities and scientific data analysis. According to Tene et al.

[2] the integration of digital technology in science learning enables students to obtain data-based and experimental learning experiences that are more accurate and efficient.

Physics as a fundamental science plays an important role in explaining natural phenomena through a systematic and empirical scientific approach. Research by Mayer et al. [3] explains that the understanding of physics concepts is not only obtained through theoretical learning in the classroom, but also through experimental activities in the laboratory that allow students to directly observe the physical phenomena being studied. Experiments become an important component in physics learning because they provide opportunities for students to develop science process skills, such as conducting measurements, controlling experimental variables, analyzing data, and drawing conclusions based on empirical evidence [4]. Through laboratory activities, students not only understand physics concepts conceptually but also gain scientific experience that supports the development of critical and analytical thinking skills.

The quality of laboratory-based physics learning is strongly influenced by the availability and quality of experimental apparatus used in laboratory activities. Research conducted by Hayuana et al. [5] shows that limitations in laboratory facilities as well as the use of conventional experimental apparatus can hinder the effectiveness of the practicum process. Experimental apparatus that still uses manual measurement methods often leads to low efficiency in data collection, an increased potential for measurement errors, and limitations in the utilization of experimental data for further analysis [6]. This condition can affect the suboptimal implementation of experiment-based learning in physics education. Previous studies indicate that the use of conventional experimental instruments remains one of the factors contributing to low measurement accuracy and limited utilization of experimental data in learning [7]. This condition is still frequently found in basic physics laboratory activities in various universities.

Similar problems are also found in optics laboratory activities, particularly in diffraction grating experiments. Diffraction grating is one of the important phenomena in optics used to determine the wavelength of light through the analysis of interference patterns formed after light passes through a diffraction grating [8]. Diffraction grating experiments are usually conducted by measuring the distance between the central bright fringe and a certain diffraction order on the observation screen. Based on preliminary observations conducted in the Basic Physics Laboratory, the process of measuring the distance of bright–dark fringe patterns in diffraction experiments is still carried out manually using a ruler. This measurement method requires a relatively long time, approximately 10–15 minutes for each diffraction order observed. In addition, manual measurements also show a relatively significant variation in measurement errors, ranging from 1–3 mm, caused by the limited precision of measuring instruments as well as the subjectivity of the observer in determining the position of maximum light intensity. This condition has the potential to reduce the accuracy level of experimental data and decrease the efficiency of laboratory activities.

Along with the development of digital technology, various innovations have begun to be developed to improve the quality of experimental apparatus in science learning. One technology that has great potential to be applied in physics experiments is the Internet of Things (IoT). IoT is a technological concept that enables various physical devices, such as sensors and microcontrollers, to be connected through internet networks so that they can exchange data automatically and in real time [9]. In the context of physics experiments, the utilization of IoT enables the data acquisition process to be conducted automatically using digital sensors integrated with network-based data processing systems. The implementation of IoT in science education has been reported to improve experimental efficiency, increase measurement accuracy, and enhance student engagement in digital data–based learning processes [10].

Several previous studies have developed sensor- and microcontroller-based experimental apparatus to support physics laboratory activities. Research conducted by Hazman et al. [11], for example, has developed an experimental apparatus to determine the wavelength of light using light sensors and ultrasonic sensors. However, the developed system is still local and has not been integrated with IoT technology, so the experimental data cannot yet be accessed online and in real time. Other studies have also developed IoT-based laboratory systems on topics in mechanics and electromagnetism, such as Newton's law experiments and electromagnetic induction [12]. Nevertheless, the application of IoT technology in optics experiments, particularly on the topic of diffraction grating, is still relatively limited. In addition, most diffraction experiments used in learning still rely on manual measurement methods that are prone to subjective errors and are less efficient in the data acquisition process.

Based on these problems, it is necessary to develop a diffraction grating experimental apparatus that is capable of performing measurements automatically and precisely and is integrated with an Internet of Things–based data acquisition system. Therefore, this study aims to develop an Internet of Things (IoT)-based diffraction grating experimental apparatus equipped with an automatic motion system using a stepper motor and a real-time light intensity graph visualization system. The development of this experimental apparatus is expected to improve the accuracy and efficiency of the measurement process in diffraction grating laboratory activities, while also supporting digital data–based physics learning [13].

The novelty of this study lies in the integration of the diffraction grating experimental system with IoT technology, which enables the diffraction pattern scanning process to be conducted automatically using a stepper motor, the measurement of light intensity using digital sensors, and the visualization of experimental data in real time through a network-based platform. Thus, the developed experimental apparatus functions not only as a measuring instrument but also as a technology-based learning medium that supports the modernization of physics laboratories and improves the quality of experimental learning in physics education.

Literature Review

a. Physics Experiment Equipment

A physics experimental apparatus is a set of instruments, measuring devices, and materials designed to conduct the observation and measurement of physical phenomena empirically. In physics learning, experimental apparatus plays an important role as a means of linking abstract theoretical concepts with concrete learning experiences. Through experimental activities, students can perform direct measurements, control experimental variables, and analyze the relationship between theory and empirical data obtained from observations [14].

Experimental activities also play a role in developing science process skills, such as observation, measurement, data interpretation, and scientific reasoning. In addition, laboratory experiments enable students to develop critical thinking skills and problem-solving abilities based on empirical evidence obtained through measurement and data analysis processes[15]. Therefore, experimental apparatus in physics learning needs to be designed systematically by considering aspects of scientific validity, practicality of use, and pedagogical effectiveness.

The development of digital technology has encouraged innovation in the design of physics experimental apparatus. The integration of sensor technology, microcontrollers, and digital data acquisition systems enables the measurement process to be conducted automatically with a higher level of accuracy [16]. Modern experimental apparatus functions not only as a measuring instrument but also as a learning medium capable of displaying experimental data in real time, thereby facilitating the process of data analysis and interpretation by students [7]. Thus, the development of digital technology–based experimental apparatus becomes an important effort in improving the quality of laboratory-based physics learning.

b. Internet of Things (IoT) in Physics Experiments

The Internet of Things (IoT) is a technological concept that enables various physical devices, such as sensors, actuators, and microcontrollers, to be connected through internet networks so that they can send, receive, and process data automatically. IoT technology generally consists of three main components, namely sensor-based physical devices as data collectors, communication networks as data transmission media, and data processing systems that function to store and analyze the obtained information [17].

In the field of science education, the application of IoT technology provides opportunities to develop more modern and efficient experimental systems. The integration of digital sensors with microcontrollers enables the measurement process to be carried out automatically, thereby reducing measurement errors caused by human factors [18]. In addition, IoT systems allow experimental data to be transmitted directly to computer devices or web-based applications so that the data can be analyzed and visualized in real time [19].

The utilization of IoT technology in physics experiments also enables the development of network-based laboratory systems that support the concepts of smart laboratories and remote laboratories. Through this system, experimental data can be accessed online, thereby expanding opportunities for the utilization of physics experiments in technology-based digital learning [20]. Therefore, the integration of IoT technology in physics experimental apparatus has great potential to improve experimental efficiency, measurement accuracy, and the quality of data analysis in laboratory activities.

c. Grating Diffraction

Diffraction is a phenomenon of wave spreading that occurs when a light wave passes through a narrow slit or an obstacle whose size is comparable to the wavelength of the light. When light passes through a diffraction grating consisting of a large number of narrow slits arranged periodically, an interference pattern in the form of bright and dark regions is formed on the observation screen. This diffraction pattern can be used to determine the wavelength of light used in the experiment [21].

The relationship between the wavelength of light, the grating constant, and the diffraction angle is expressed by the fundamental equation of diffraction grating:

$$d sin\theta = m\lambda \quad (1)$$

with:

- d = lattice constant (distance between slits)
- θ = diffraction angle
- m = diffraction order (m = 0, 1, 2, 3, ...)
- λ = wavelength of light

The lattice constant ddd is related to the number of lattice lines per unit length of the NNN, so it can be expressed as:

$$d = \frac{1}{N} \quad (2)$$

where N is the number of slits per unit length in the diffraction grating.

In laboratory grating diffraction experiments, the diffraction angle θ is usually not measured directly, but is calculated based on the geometric relationship between the distance of the m-order bright to the central bright and the distance between the grating and the observation screen. If x is the distance between the central bright and the m-order bright, and L is the distance between the diffraction grating and the observation screen, then the sine value of the diffraction angle can be expressed as:

$$sin\theta = \frac{x}{\sqrt{x^2+L^2}} \quad (3)$$

By substituting this equation into the grating diffraction equation, the relationship between the wavelength of light and the experimental parameters is obtained as follows:

$$\lambda = \frac{d}{m} \cdot \frac{x}{\sqrt{x^2+L^2}} \quad (4)$$

with:

- x = the distance between the central light and the mmm-th order light
- L = distance between the diffraction grating and the screen
- m = diffraction order
  - This equation is the basis for analyzing grating diffraction experiments to determine the wavelength of light based on measurement data obtained during the practicum[22]. In the context of physics learning, grating diffraction experiments provide empirical experience to students to understand the nature of light waves and verify the relationship between theoretical models and experimental data obtained through measurements.

Method

This research uses a Research and Development (R&D) approach which aims to develop an Internet of Things (IoT)-based physics experimental apparatus on the topic of diffraction grating and to test its feasibility and practicality in physics laboratory activities. The research and development method is used to produce a product in the form of an experimental apparatus that can be used as a learning medium as well as a measuring instrument in laboratory practicum activities.

The development process of the apparatus is carried out by referring to the ADDIE model (Analysis, Design, Development, Implementation, Evaluation). The ADDIE model is chosen because it provides a systematic and flexible framework in designing and developing technology-based learning products. This model is also widely used in the development of instructional media and educational experimental apparatus because it is able to integrate the processes of needs analysis, system design, product development, implementation, and evaluation in a structured manner [23].

a. Development Procedure

The development of the IoT-based diffraction grating experimental apparatus in this research is conducted through five main stages in accordance with the ADDIE model.

1. Analysis

The analysis stage is conducted to identify the needs for developing experimental apparatus in basic physics laboratory activities. At this stage, several aspects are analyzed, namely:

a) practicum needs in diffraction grating experiments,
b) limitations of conventional experimental apparatus used in the laboratory,
c) as well as the potential utilization of sensor technology and IoT in improving measurement efficiency and accuracy.

The results of the analysis show that the measurement of diffraction patterns which is still conducted manually has a relatively high level of error and requires a relatively long measurement time. Therefore, it is necessary to develop an experimental apparatus that is capable of performing measurements automatically and displaying experimental data digitally.

2. Design

The design stage is conducted to develop the system design of the experimental apparatus that will be developed. At this stage, the main components of the experimental apparatus are determined, including the light source, diffraction grating, light detector system, sensor driving system, and IoT-based data communication system.

he design of the experimental apparatus system consists of three main modules, namely:

a) Optical module, which consists of a laser diode light source and a diffraction grating to produce diffraction patterns on the observation screen.
b) Data acquisition module, which uses an LDR light sensor to detect light intensity and an ultrasonic sensor to measure the position of the detector relative to the diffraction screen.
c) Control and data communication module, which uses a NodeMCU ESP8266 microcontroller to control the stepper motor and transmit experimental data through the internet network.

This stage also includes the design of the detector motion mechanism using a stepper motor which allows the light sensor to move automatically along the screen to scan the bright and dark patterns produced by the diffraction grating.

3. Development

The development stage is the process of realizing the system design that has been previously designed into an experimental apparatus that can be used in laboratory activities. At this stage, the process of assembling the hardware and developing the software required to operate the experimental system is carried out.

The hardware used in this system includes a laser diode as the light source, a diffraction grating as the medium for forming interference patterns, an LDR light sensor as a light intensity detector, an ultrasonic sensor as a position measurement device, a stepper motor as the detector driving system, and a NodeMCU ESP8266 microcontroller as the central control system. The microcontroller is programmed to control the movement of the stepper motor, read sensor data, and transmit experimental data to the IoT system through a Wi-Fi network.

In addition, the system is also equipped with a data visualization interface that allows users to monitor measurement results in real time in the form of a graph showing the relationship between light intensity and measurement position.

4. Implementation

The implementation stage is conducted to test the function of the experimental apparatus that has been developed under laboratory conditions. At this stage, the apparatus is used to measure the diffraction pattern of light passing through a diffraction grating so that data on the position and light intensity produced from each diffraction order are obtained.

In addition to performance testing of the apparatus, this stage also involves the product validation process by subject matter experts and media/instrumentation experts to assess the feasibility of the developed experimental apparatus.

5. Evaluation

The evaluation stage is conducted to assess the feasibility and practicality level of the experimental apparatus that has been developed. The evaluation is carried out based on the results of expert validation and user responses to the experimental apparatus used in laboratory activities. The evaluation results are used as a basis to determine whether the developed experimental apparatus meets the feasibility criteria as a physics laboratory learning medium.

b. Research Instruments

The instruments used in this research include expert validation sheets and user response questionnaires. The validation sheet is used to assess the feasibility of the developed experimental apparatus based on material aspects and media aspects.

Material expert validation includes several assessment aspects, namely:

1. the suitability of the diffraction grating concept,
2. the clarity of experimental procedures,
3. the suitability with learning objectives,
4. as well as the completeness of practicum materials.

Meanwhile, media expert validation includes an assessment of the technical aspects of the apparatus, such as instrument design, sensor performance, safety of use, and the ease of operating the experimental apparatu.

c. Data Analysis Technique

The data obtained in this research are quantitative data obtained from expert validation results and user responses to the developed experimental apparatus. The assessment data are collected using a Likert scale with a score range of 1 to 4, namely:

1. score 4: very good / strongly agree
2. score 3: good / agree
3. score 2: less good / less agree
4. score 1: very poor / strongly disagree

The feasibility level of the experimental apparatus is calculated using the percentage score with the following formula:

Table 1. Value Intervals for Media Suitability Levels

Percentage	Criteria
80% – 100%	Very Eligible
66% – 79%	Eligible
56% – 65%	Less Eligible
0% – 55%	Not Eligible

Result and Discussion

The development of an Internet of Things (IoT)-based diffraction grating experimental apparatus produces an experimental system capable of automatically scanning diffraction patterns and displaying light intensity data in real time. The analysis of the research results focuses on the design and implementation of the developed apparatus, the results of feasibility validation by experts, system performance testing in detecting diffraction patterns, as well as the analysis of experimental results and their implications for laboratory-based physics learning.

a. Design and Implementation of IoT-Based Diffraction Grating Experimental Apparatus

The development of an Internet of Things (IoT)-based diffraction grating experimental apparatus was carried out to improve the efficiency and accuracy of the diffraction pattern measurement process in physics laboratory activities. The developed apparatus was designed to replace the manual measurement method that has been commonly used in diffraction grating experiments. In the conventional method, the measurement of the distance between the central bright fringe and a particular diffraction order is performed using a ruler directly on the observation screen. According to Jia et al. [13] this method has several limitations, including susceptibility to parallax errors, relatively long measurement time, and dependence on the observer's subjectivity in determining the position of maximum light intensity. Therefore, the experimental apparatus in this study was designed by utilizing sensor technology and an IoT-based data acquisition system so that the measurement process can be conducted automatically and with greater precision.

The developed experimental apparatus consists of several main components integrated into a single system. These components include a light source in the form of a laser diode with a wavelength of approximately 650 nm, a diffraction grating as the medium for forming interference patterns, an observation screen where the diffraction pattern is formed, and a detector unit equipped with a light sensor. The light sensor used in this study is a Light Dependent Resistor (LDR) which functions to detect the light intensity at each measurement point along the diffraction pattern. This sensor is placed on a detector unit that can move linearly so that it is capable of scanning changes in light intensity from bright regions to dark regions in the diffraction pattern.

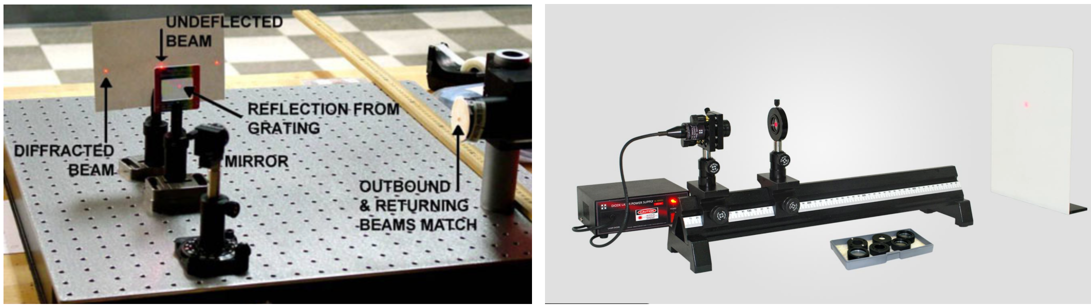

Figure 1. IoT-Based Grating Diffraction Experimental Device Set

To enable the automatic scanning process of the diffraction pattern, the detector unit is designed to move along a linear rail using a stepper motor drive system. The stepper motor is controlled by a microcontroller so that the movement of the sensor can be regulated precisely with specific steps in each measurement process. With this mechanism, the light sensor can perform gradual scanning at various positions along the observation screen. Each change in the sensor position is followed by the process of reading the light intensity by the LDR sensor, resulting in data on the light intensity distribution that forms the diffraction pattern.

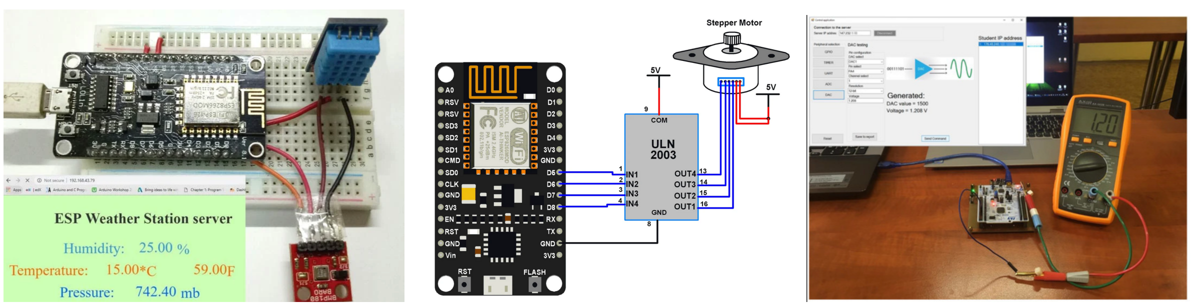

Figure 2. NodeMCU ESP8266 Based Control System Circuit

The control system of the experimental apparatus uses a NodeMCU ESP8266 microcontroller which has wireless communication capability through a Wi-Fi network. This microcontroller functions as the central control unit that regulates the movement of the stepper motor, reads light sensor data, and transmits measurement data to an IoT-based monitoring system [24]. he selection of the NodeMCU ESP8266 is based on its ability to integrate microcontroller functions and internet communication modules within a single device, thereby facilitating the development process of IoT-based experimental systems.

At the system implementation stage, the microcontroller is programmed to perform several main functions in an integrated manner. First, the microcontroller controls the movement of the stepper motor that drives the detector unit along the linear rail. Second, the microcontroller reads the resistance value of the LDR sensor which changes according to the intensity of the received light. The resistance value is then converted into light intensity data that can be further analyzed. Third, the light intensity data obtained from the sensor are transmitted wirelessly through a Wi-Fi network to a computer device or a web-based monitoring application. Through this system, users can monitor the measurement results in real time without having to perform manual recording.

In addition to supporting the automatic data acquisition process, the implemented IoT system also enables the visualization of experimental data in the form of a graph showing the relationship between light intensity and measurement position. This visualization facilitates users in identifying the positions of maximum light intensity that indicate the diffraction order maxima. Thus, the analysis process of diffraction patterns can be conducted in a more systematic and objective manner compared to direct visual observation methods.

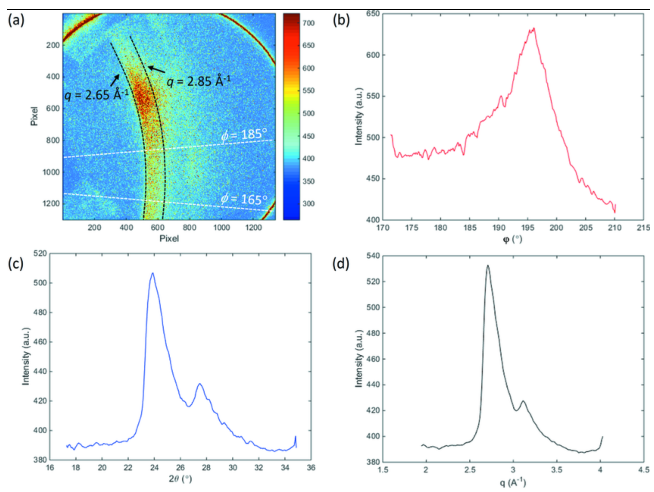

Figure 3. Graph of Light Intensity Distribution Against Measurement Position

Based on the light intensity distribution graph in Figure 3, there is an intensity peak that indicates the position of the diffraction order brightness. The highest intensity peak is at the center brightness (0th order), while the next peaks indicate the first order brightness and subsequent orders with decreasing intensity. The results of the quantitative analysis of the intensity peak position are shown in Table 2.

Table 2. Parameters of the Results of the Analysis of Light Intensity Distribution in the Diffraction Pattern

Diffraction Order (m)	Peak Position (x)	Maximum Intensity (a.u.)	Peak Width (FWHM)	Information
0	0.00	525	0.32	Central light
1	2.65	510	0.41	First-order peak
2	2.85	495	0.38	Second-order peak
3	3.10	470	0.46	Intensity begins to decrease

The data indicate that the distribution of light intensity obtained from the sensor system exhibits a pattern consistent with the theoretical characteristics of diffraction grating, where maximum intensity occurs in the bright regions and gradually decreases at higher diffraction orders.

The results of the system implementation show that the experimental apparatus is capable of automatically scanning the diffraction pattern with controlled position intervals. The light intensity data obtained from the sensor form an intensity distribution pattern that corresponds to the characteristics of diffraction grating patterns, namely intensity peaks in bright regions and a decrease in intensity in dark regions [25]. This intensity distribution pattern can be used to determine the positions of diffraction order maxima more precisely compared to the manual measurement method.

The integration of IoT technology in the experimental apparatus also provides advantages in terms of data acquisition efficiency. The measurement process, which previously required approximately 10–15 minutes for each diffraction order, can be shortened because the system automatically performs scanning along the diffraction pattern. In addition, the use of digital sensors is able to reduce measurement errors caused by the subjectivity of the observer. Thus, the developed experimental apparatus not only improves measurement accuracy in diffraction grating experiments but also supports the development of more modern and digitally based physics laboratories.

b. Eksperimen Experimental Device Feasibility Validation Results

The feasibility validation of the Internet of Things (IoT)-based diffraction grating experimental apparatus was conducted to ensure that the developed apparatus meets conceptual, technical, and pedagogical aspects before being used in physics laboratory activities. The validation process was carried out by two groups of experts, namely physics subject-matter experts and media/ instrumentation experts. Validation by subject-matter experts aims to assess the suitability of the physics concepts used in the experimental apparatus, while validation by media experts aims to evaluate the quality of the apparatus design, the performance of the electronic system, and the ease of use of the instrument in the context of laboratory practicum activities.

The feasibility assessment was conducted using an instrument in the form of a validation sheet with a four-level Likert scale, namely very good (4), good (3), less good (2), and very poor (1). The obtained scores were then converted into percentages of feasibility level using the percentage score formula. The interpretation of the validation results refers to the criteria for the feasibility of instructional apparatus that have been determined in the research methods section.

1. Validation Results by Material Experts

Validation by subject matter experts focused on the suitability of the grating diffraction concept implemented in the experimental device and its relevance to physics learning objectives. Several aspects assessed included the suitability of the theoretical concept, the clarity of the experimental procedure, its relevance to the learning outcomes of the practical work, and the device's potential to help students understand the concept of light diffraction.

Table 3. Results of Validation of the Feasibility of Experimental Devices by Material Experts

No	Assessment Aspect	Score Obtained	Percentage (%)	Category
1	Suitability of the grating diffraction concept	4	100	Very Worthy
2	Clarity of the experimental procedure	3	75	Worthy
3	Suitability to the objectives of the practicum	4	100	Very Worthy
4	Potential for improving conceptual understanding	3	75	Worthy
5	Accuracy of the experimental data	4	100	Very Worthy
Average			**90**	**Very Worthy**

Based on the data in Table 3, the average feasibility score obtained is 90%, which falls into the very feasible category. These results indicate that the developed experimental apparatus has fulfilled the conceptual aspects required in diffraction grating experiments. The highest assessment was given to the aspects of the suitability of the diffraction grating concept and the accuracy of the experimental data, indicating that the apparatus is capable of representing the diffraction phenomenon scientifically in accordance with optical theory [21].

Meanwhile, the aspects of the clarity of experimental procedures and the potential for improving conceptual understanding obtained scores in the feasible category. This indicates that although the apparatus is conceptually appropriate, there are still opportunities for improvement in the preparation of laboratory guidelines so that students can more easily understand the experimental procedures carried out.

2. Validation Results by Media and Instrumentation Experts

Validation by media experts focused on the technical aspects of the experimental device, including tool design, electronic system integration, safety of use, and ease of operation in a laboratory environment.

Table 4. Experimental Device Feasibility Validation Results by Media Experts

No	Assessment Aspect	Score Obtained	Percentage (%)	Category
1	Experimental device design	3	75	Worthy
2	Sensor performance and data acquisition	4	100	Very Worthy
3	IoT system integration	4	100	Very Worthy
4	Device safety	3	75	Worthy
5	Ease of operation	4	100	Very Worthy
Average			**90**	**Very Worthy**

The results in Table 4 show that the experimental apparatus obtained an average feasibility score of 90%, which falls into the very feasible category. The aspects with the highest assessment are sensor performance and IoT system integration. This indicates that the developed system is capable of performing the data acquisition process automatically and transmitting experimental data in real time through the internet network [26].

In addition, the ease of operation of the apparatus also received a very feasible assessment, indicating that the experimental apparatus can be used practically in laboratory activities. However, the aspects of apparatus design and operational safety still fall into the feasible category, therefore there are recommendations from the validators to improve the arrangement of electronic components as well as the protection of components from disturbances in the laboratory environment.

3. Recapitulation of Device Eligibility Validation Results

To obtain a comprehensive picture of the feasibility of the experimental device developed, the validation results from material experts and media experts were then summarized as shown in Table 4.

Table 5. Recapitulation of Experimental Device Feasibility Validation Results

Validator	Eligibility Percentage (%)	Category
Material expert	90	Very Worthy
Media expert	90	Very Worthy
Overall average	**90**	**Very Worthy**

Based on the recapitulation in Table 5, the average feasibility score of the apparatus is 90%, which falls into the very feasible category. These results indicate that the developed IoT-based diffraction grating experimental apparatus has fulfilled the feasibility criteria both in terms of physics concepts and the technical aspects of the apparatus. Therefore, this experimental apparatus is considered feasible to be used in basic physics laboratory activities.

Overall, the validation results indicate that the integration of sensor technology and IoT systems in the experimental apparatus is capable of producing a laboratory system that is not only scientifically accurate but also practical to be used in an educational laboratory environment. The validation by experts also indicates that the developed apparatus has the potential to improve the quality of physics experimental learning through a measurement process that is more objective, efficient, and based on digital data.

c. Difraksi Testing Device Performance in Measuring Diffraction Patterns

The performance testing of the Internet of Things (IoT)-based diffraction grating experimental apparatus was conducted to evaluate the system's ability to detect the distribution of light intensity and to determine the positions of diffraction order maxima accurately. This testing aims to determine the extent to which the developed apparatus is capable of replacing the manual measurement method that has been commonly used in optics laboratory activities. In addition, the testing was also conducted to assess the consistency of the data obtained from the sensor system as well as the conformity of the produced diffraction pattern with diffraction grating theory.

The experiment was conducted using a light source in the form of a laser diode with a wavelength of approximately 650 nm directed toward the diffraction grating. The light passing through the diffraction grating undergoes diffraction and interference processes, forming bright and dark patterns on the observation screen. The detector unit equipped with a light sensor then moves along a linear rail using a stepper motor to scan the distribution of light intensity on the screen. Each change in the detector position is followed by the reading of light intensity values by the LDR sensor, which are then transmitted to the monitoring system through the NodeMCU ESP8266 microcontroller.

The data obtained from the sensor scanning process are recorded in the form of paired values of position and light intensity. These data are then analyzed to obtain a graph of light intensity distribution with respect to the measurement position. This graph provides an overview of the structure of the diffraction pattern formed, where the peaks of the graph indicate bright regions with maximum intensity, while the valleys of the graph indicate dark regions with lower intensity.

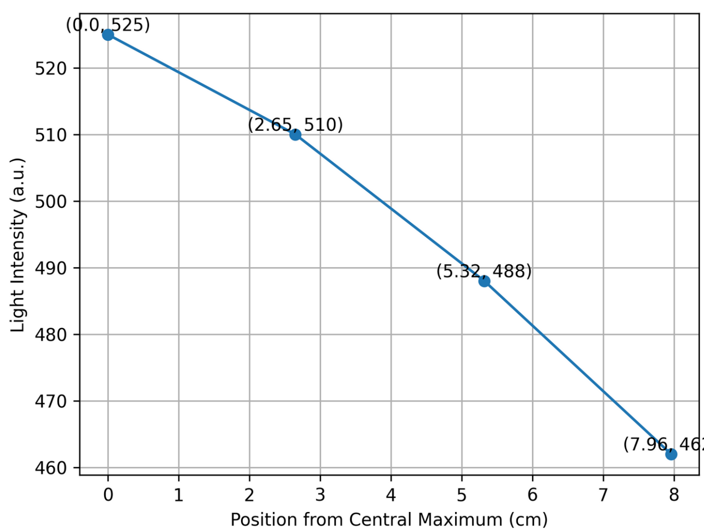

Figure 4. Graph of Light Intensity Distribution Against Measurement Position on the Grating Diffraction Pattern

Gambar 4 menunjukkan distribusi Figure 4 shows the distribution of light intensity with respect to the measurement position obtained from the sensor scanning process on the diffraction screen. Each point on the graph represents the maximum intensity value detected by the light sensor at a particular position along the observation screen. Based on the graph, it can be seen that the highest light intensity occurs at the central maximum (zero-order diffraction) with an intensity value of 525 relative units. Subsequently, at the following diffraction orders there is a gradual decrease in light intensity, namely 510 for the first order, 488 for the second order, and 462 for the third order.

The intensity distribution pattern shown in the graph is consistent with the theoretical characteristics of diffraction grating. In the diffraction phenomenon, most of the light energy is concentrated at the central maximum, while at higher diffraction orders the light intensity decreases due to the distribution of energy spreading in various directions after passing through the grating slits [27]. Thus, the higher the observed diffraction order, the smaller the detected light intensity tends to be.

In addition to showing variations in light intensity, the graph also illustrates the relationship between the measurement position and the diffraction order formed. The positions of diffraction order maxima that are farther from the central maximum indicate that the diffraction angle increases with increasing diffraction order. This is consistent with the fundamental diffraction grating equation, which states that the diffraction angle is proportional to the diffraction order for a given light wavelength and grating constant [13].

The light intensity measurement results shown in the graph also indicate that the sensor system used in the experimental apparatus is capable of detecting variations in light intensity consistently at different measurement positions. The gradually decreasing intensity values indicate that the scanning process performed by the detector unit using the stepper motor operates stably in reading the distribution of light intensity in the diffraction pattern. This indicates that the data acquisition system integrated with the light sensor and microcontroller is capable of producing experimental data that represent the diffraction pattern formed.

Overall, the intensity distribution graph in Figure 4 provides evidence that the developed experimental apparatus is capable of automatically recording the characteristics of diffraction patterns and producing measurement data that are consistent with the theory of light diffraction. With the implementation of a sensor-based scanning system and the integration of IoT technology, the experimental data acquisition process can be carried out more efficiently and objectively compared to manual measurement methods that rely on visual observation [28].

In addition to the analysis of light intensity distribution, the performance testing of the apparatus was also conducted by analyzing the relationship between the positions of diffraction order maxima and their distances from the central maximum. This relationship is important for determining the experimental parameters used in calculating the wavelength of light.

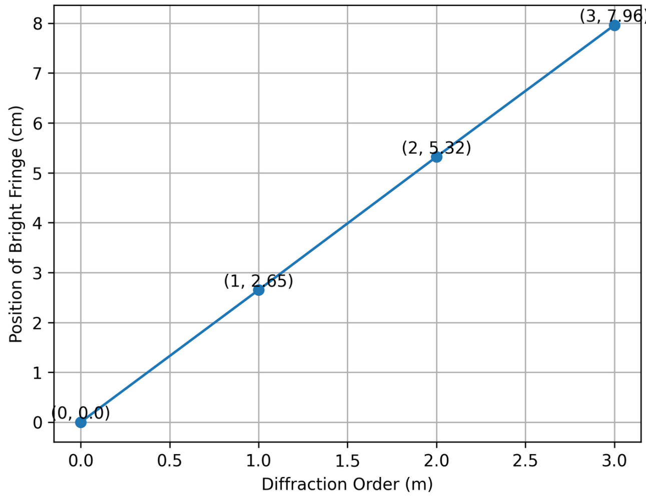

Figure 5. Relationship between Diffraction Order and Bright Position of Sensor Measurement Results

Figure 5 shows the relationship between the diffraction order and the position of the bright fringe detected by the sensor on the observation screen. Each point on the graph represents the position of the maximum light intensity corresponding to a particular diffraction order. Based on the graph, it can be observed that the position of the bright fringe increases with increasing diffraction order. The central maximum (zero order) is located at position zero, while the first, second, and third diffraction order maxima are detected at positions progressively farther from the center of diffraction.

This relationship shows an almost linear tendency between the diffraction order and the distance of the bright fringe position from the center of diffraction. This pattern is consistent with diffraction grating theory, which states that the diffraction angle increases with increasing diffraction order for a given light wavelength and grating constant. As the diffraction angle increases, the position of the bright fringe on the observation screen also moves farther away from the central maximum.

The consistency of the relationship between diffraction order and bright fringe position shown in the graph indicates that the developed experimental apparatus is capable of detecting the positions of diffraction maxima in a stable and systematic manner [29]. his indicates that the scanning mechanism using the stepper motor as well as the light intensity reading system by the sensor can function properly in measuring diffraction patterns.

To obtain an overview of the measurement results produced by the experimental apparatus, the data on bright fringe positions and light intensity are then summarized in the form of a table as shown in Table 5..

Table 5. Results of Measurement of Bright Position and Light Intensity in Diffraction Patterns

Orde Difraksi (m)	Posisi Terang (cm)	Intensitas Maksimum (a.u.)
0	0.00	525
1	2.65	510
2	5.32	488
3	7.96	462

Based on the data in Table 5, the maximum intensity is found at the central brightness, while the light intensity decreases at higher diffraction orders. This decrease in intensity is a common characteristic of grating diffraction patterns, indicating that light energy is distributed in various directions after passing through the grating slits.

Furthermore, the results of the brightness position measurements show an almost linear increase in distance with the diffraction order. This indicates that the experimental device is capable of consistently detecting the brightness position at various diffraction orders. This consistency in data demonstrates that the sensor system and scanning mechanism using a stepper motor are capable of performing well in measuring the position of the diffraction pattern.

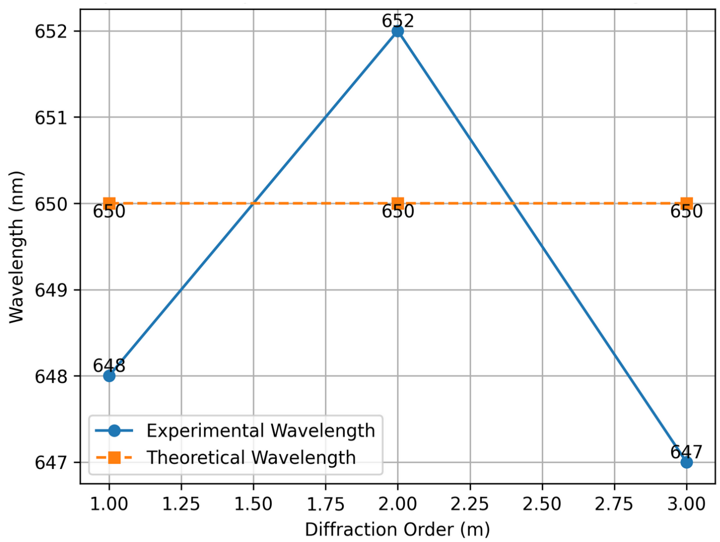

Figure 6. Comparison of the Wavelength Values of Light from Experimental Measurements with the Theoretical Values at Various Diffraction Orders

Figure 6 shows the comparison between the wavelength values obtained from the experimental results and the theoretical value of the light source used in the experiment. The experimental wavelength values were calculated based on the diffraction maxima position data obtained from the sensor scanning results, while the theoretical value refers to the wavelength of the laser diode used as the light source in the experiment.

Based on the graph, it can be observed that the experimental wavelength values show a tendency that is very close to the theoretical value of 650 nm. At the first diffraction order, the wavelength value obtained is 648 nm, at the second order 652 nm, and at the third order 647 nm. The small differences between the experimental values and the theoretical value indicate measurement deviations that are still within the tolerance limits of educational laboratory experiments.

The small differences between the experimental and theoretical values may be caused by several factors, including the precision of the light sensor in detecting maximum intensity, the resolution of the stepper motor movement in the scanning system, as well as possible minor errors in determining the position of the maximum intensity in the light intensity distribution graph. Nevertheless, these differences are relatively small, indicating that the developed experimental apparatus is capable of producing sufficiently accurate measurements.

The agreement between the experimental results and the theoretical value indicates that the developed experimental system is able to represent the diffraction grating phenomenon properly [30]. In addition, the integration of the light sensor, automatic scanning system, and Internet of Things–based data acquisition allows the measurement process to be conducted in a more systematic and objective manner compared to manual observation method.

d. Analysis of Experimental Results and Learning Implications

The analysis of diffraction grating experimental results was conducted to evaluate the conformity of the measurement data obtained from the experimental apparatus with the theoretical concept of light diffraction. In addition, this analysis also aims to determine the level of accuracy of the developed apparatus and its implications for experiment-based physics learning. The data obtained from the sensor scanning system in the form of diffraction order maxima positions and light intensity values were then used to calculate experimental parameters, particularly the wavelength of the light used in the experiment.

The wavelength calculation was performed using the diffraction grating equation that relates the grating constant, the diffraction angle, and the diffraction order. The diffraction angle value was obtained from the geometric relationship between the distance of the bright fringe from the central maximum and the distance between the diffraction grating and the observation screen. By using the bright fringe position data obtained from the sensor scanning results, the wavelength value of the light can be calculated for each observed diffraction order.

Table 6. Results of Calculation of Light Wavelength Based on Experimental Data

Diffraction Order (m)	Brightness Position (cm)	Diffraction Angle (°)	Wavelength (nm)
1	0,12847222	04.05	648
2	05.32	08.10	652
3	0,35833333	12.12	647

Based on the data in Table 6, the experimental wavelength values were in the range of 647–652 nm, with an average value approaching 650 nm. This value is very close to the theoretical wavelength of the laser diode used as the light source in the experiment. The close proximity between the experimental and theoretical values indicates that the developed experimental device is capable of producing fairly accurate measurement data. Small variations in the wavelength values obtained at each diffraction order may be due to the light sensor's accuracy in detecting maximum intensity and the stepper motor's resolution in determining the measurement position.

To determine the accuracy of the measurement results, a relative error analysis was performed by comparing the experimental wavelength values with the theoretical values of the light source used. The results of the relative error analysis are shown in Table 7.

Table 7. Relative Error Analysis of Wavelength Measurement Results

Diffraction Order (m)	λ Experiment (nm)	λ Theoretical (nm)	Error (%)
1	648	650	0.31
2	652	650	0.31
3	647	650	0.46

The data in Table 7 shows that the relative measurement error ranges from 0.31% to 0.46%. This relatively small error value indicates that the experimental device has a good level of accuracy for use in physics labs. The remaining measurement errors are likely caused by several factors, such as the resolution of the light sensor readings, the accuracy of the stepper motor movement mechanism, and possible fluctuations in light intensity in the laser source used.

In addition to quantitative analysis of the measurement results, this study also analyzed the efficiency of using the experimental device compared to conventional lab methods. Manual measurements in grating diffraction labs are typically time-consuming because students must visually determine the brightness and measure using a ruler. By using an IoT-based experimental device, the diffraction pattern scanning process can be automated, thereby shortening data collection time[31].

Table 8. Comparison of Conventional Diffraction Experiment Methods and IoT-Based Experimental Devices

Aspects	Conventional Methods	IoT Devices
Measurement method	Manually using a ruler	Automatic sensor
Measurement time	10–15 minutes per order	±2 minutes
Measurement accuracy	Depends on the observer	More consistent
Data processing	Recorded manually	Automatic and real-time
Result visualization	Direct observation	Digital graph

Based on Table 8, it can be seen that the IoT-based experimental apparatus has several advantages compared to conventional practicum methods. One of the main advantages is the system's ability to perform automatic data acquisition and display measurement results in the form of digital graphs. This facilitates students in analyzing experimental data because the distribution of light intensity can be directly observed through graphical visualization.

In addition to improving practicum efficiency, the use of IoT-based experimental apparatus also has a positive impact on the physics learning process. With the presence of an automatic scanning system and real-time data visualization, students can more easily understand the relationship between the theoretical concept of light diffraction and the experimental data obtained in the laboratory [32]. The graphical visualization of light intensity distribution allows students to identify the positions of diffraction order maxima more objectively compared to direct visual observation.

From a pedagogical perspective, the developed experimental apparatus also supports an inquiry-based and data-driven learning approach. Students can explore experimental data, analyze the relationship between experimental parameters, and compare measurement results with theoretical models studied in lectures. Thus, this experimental apparatus functions not only as a measuring instrument but also as a learning medium capable of increasing student engagement in experiment-based learning processes.

Overall, the analysis of the experimental results indicates that the developed Internet of Things–based diffraction grating experimental apparatus is capable of producing measurement data that are accurate and consistent with the theory of light diffraction. In addition, the integration of sensor technology and digital data acquisition systems provides a positive contribution to improving the quality of physics laboratory activities through measurement processes that are more efficient, objective, and based on digital data. This indicates that the implementation of IoT technology in physics experimental apparatus has great potential to support the modernization of educational laboratories and to enhance the quality of experiment-based physics learning.

Conclusion

This study successfully developed an Internet of Things (IoT) based diffraction grating experimental apparatus capable of automatically measuring diffraction patterns and displaying light intensity data in real time. The developed device consists of a laser light source, diffraction grating, light sensor, stepper motor drive system, and a NodeMCU ESP8266 microcontroller integrated into a digital data acquisition system.

The validation results by material experts and media experts indicate that the experimental apparatus falls into the very feasible category for use in physics laboratory activities. The performance testing of the device also shows that the system is capable of consistently detecting the distribution of light intensity and the positions of diffraction maxima. The calculation of the light wavelength obtained from the experimental data ranges from 647–652 nm, which is close to the theoretical value of the light source wavelength of 650 nm, with a relatively low level of error.

In addition to improving measurement accuracy, the IoT-based experimental apparatus also enhances the efficiency of laboratory activities because data acquisition can be performed automatically and visualized in the form of digital graphs. Therefore, the developed experimental apparatus functions not only as a measurement instrument but also as a learning medium that supports experiment-based physics learning and data analysis.

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