Implementing a Raspberry Pi Based Digital Measurement System to Foster STEM Education

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Abstract

This paper reports on our achievements in promoting STEM education in upper secondary school by implementing a Digital Measurement System consisting of Raspberry Pi as a low-cost single-board computing device along with a wide range of high-accuracy yet inexpensive sensors for conducting STEM activities [1]. We investigate on both hardware and software capabilities to enable the integration of STEM disciplines through active learning approaches in authentic learning environments so as to meet the requirements of key characteristics of integrated STEM [2]. As technology integrator, the Digital Measurement System based on Raspberry Pi (DMSRP) provides students with a rich learning environment including a variety of scientific and engineering practices that encompass designing and building real electric circuits, configurating the corresponding open-source software PhyPiDAQ-package [3] for the purpose of solving real-problems, and collect, display and store the measured quantities from sensors. Moreover, the features offered by DMSRP promote content and context STEM integration making it possible to generate multiple graphical representations, including real-time visualisations in which students can analyse and apply the measurements in different forms and use them as vectors for models and modelling processes. As an example, we show how DMSRP supports integrated STEM instructions to investigate the Fraunhofer diffraction at a single slit. Within a Project-Based Learning context, engineering design approaches are adopted aiming at supporting students to create their own inexpensive diffraction scanner. They conduct real-time graphing of the diffraction pattern, record the intensity of diffraction fringes while manipulating the apparatus, and employ various mathematical concepts and methods to model mathematically physical processes based on the recorded data. In addition, we investigate different inter- and multi-disciplinary approaches to integrate STEM contents and contexts in DMSRP based environment that support collaborative learning and meaningful communication leading to a continuous growth in students' intrinsic motivation.

Keywords: *STEM, Digital Measurement System, Raspberry Pi, Project-Based Learning*

1. Introduction

In this paper, we analyse the multi-faceted implementation of the Digital Measurement Systems Based on Raspberry Pi or DMSRP to foster integrated STEM education at the K-12 level. Based on the single-board computer Raspberry Pi, the DMSRP can be integrated as technological tool and educational resource in a variety of STEM environments designed around authentic problems as context for learning. Along with the opensource software package PhyPiDAQ [3] containing a range of classes programmed in Python for the communication of the Raspberry Pi with various sensors, we explore the ways the DMSRP promotes the key characteristics of integrated STEM education [2]. Given the capabilities of the DMSRP to acquire, display, and store data obtained from various accurate yet inexpensive physical sensors through various real experimental apparatus settings, we investigate how DMSRP supports structured and iterative engineering design approaches to promote a continuous design-assessment-redesign cycle to reach the desired goal. Additionally, we look into the development of engineering and technological knowledge and skills including creativity and critical thinking in a technology-rich environment, where students interact directly with devices they purposely integrate into their own designed and conducted applications. In the context of solving engineering problems, the DMSRP facilitates the integration of mathematical and science contents by means of the crosscutting concepts built around some core ideas across different disciplines [4]. Various mathematical concepts and methods such as constructing and reasoning with equations, building functions to model relationship between quantities or employing numerical methods are used to model mathematically different physical processes based on the recorded data. Interesting approaches on how to integrate STEM contents through interdisciplinary and multidisciplinary approaches [5] in contextualised learning environments are investigated. In the framework of STEM integrated learning, students are engaged in activities based on constructivist approaches such as inquiry-based, problem- and project- based learning. We investigate how DMSRP provides immediate feedback by visualising the signal from sensors in real-time allowing learners to examine and revise their knowledge building through processes that supports articulation and reflection. Other features of the DMSRP such as supporting social learning, alternative teaching or learning beyond the classroom are analysed in the light of the new educational challenges [6]. Therefore, the DMSRP together with the opensource software PhyPiDAQ-package can offer an open learning environment possible to be implemented anytime and anywhere. As such, educators and learners can access and share information such as ready-to-use configured .daq files for different measurement tasks with specific sensors, collected data, pictures and videos to design customized learning contents [7]. In addition, the DMSRP can be integrated with web-based interactive notebooks such as JupyterLab and Jupyter Notebook, allowing users to configure and arrange workflows including experimental description with images and videos, performing scientific processing of the collected measurements, scientific computing and simulation of physical processes. Furthermore, the DMSRP system can be extended by including new sensors, offering the users the freedom to select the appropriate application modules tailored to their tasks and interests. Network tools can be used directly on the Raspberry Pi allowing users to exchange information, and enabling learning with the DMSRP to support the requirements of ubiquitous learning across *place of study* (home, school), *educational stage, type of learning* (formal and informal), *and personal ability* (special and advanced students) [8].

2. Understanding DMSRP and Its Benefits for STEM

The Digital Measurement System based on Raspberry Pi or DMSRP provides students with a variety of technological resources to conduct scientific and engineering projects and experiments that encompass activities like designing and building real electronic circuits and configurating the correlated open-source software PhyPiDAQ-package to collect, display and store the measured quantities from sensors for the purpose of solving real-problems. The Raspberry Pi is a low-cost single-board computer and has powerful computation capability based on the Raspberry Pi OS operating system. It is equipped with general-purpose input/output GPIO pins for interacting with small electronic devices such as sensor modules and actuators reacting to the changes of different physical quantities. Digital sensors for measuring distance, voltage, electric current, acceleration, magnetic induction, temperature, etc., have an I^2C-compatible interface allowing the transmission of measured data to the Raspberry Pi via the GPIO. Analog sensors need to be interfaced with the Raspberry Pi GPIO via an analog-to-digital converter, such as the ADS1115 device, for converting analog values into digital data [7]. The data acquisition, display, and record start with the graphical user interface *phypi.py* of the software package PhyPiDAQ, where the students can choose and edit different configuration files with the extension .daq for recording measured data, as well as specific configurations for devices and sensors having the extension .yaml. The features of various sensors such as number and type of channels, or measuring ranges are considered, when students configure the interface according to the experimental purposes. In order to configure the graphical display of the measurements in the window of the *.daq* file, students select specific built-in commands such as the *DataLogger*-module to display the graph of measured quantities over time, *DataGraph*-module for instant bar charts of measured signals to quickly compare data and to emphasize particular values at any instants, or the XY-graphical relationship of physical quantities if using multiple channels or sensors at the same time. Other data visualization capabilities, like introducing title, measurement name and units, proper graphical ranges, as well as the conversion of the output sensors' voltage into physical quantities or use of formulae for displaying desired quantities are provided. In addition, the PhyPiDAQ software enables the storage of the measured data, which can easily be analysed with spreadsheets such as the LibreOffice running directly on the Raspberry Pi.

3. Emphasising the Potential of DMSRP as Integrator of STEM Subjects

The DMSRP is a powerful instructional tool that supports situated learning [9] of crosscutting concepts in a rich educational environment built around core ideas of STEM subjects including science and engineering practices. Various sensors have been integrated with the DMSRP to generate meaningful real-world based, student-led and student-centred educational activities across STEM disciplinary areas targeted for different age levels.

To design and conduct instructions based on DMSRP, engineering design approaches based on circularly sequenced multiple stages commonly promote STEM learning. The knowledge building evolves through practices involving students' investigation of the problem to solve, deciding on devices they need to employ, designing schematic diagrams, building the real circuit, configuring the PhyPiDAQ software for the purpose of measurement, processing and analysing data, evaluating and communicating results. The DMSRP facilitates all these activities allowing students to move back-and-forth among problem to be solved, theory, design and resources. Furthermore, students can generate a number of possible solutions to a given problem, depending on the characteristic of the sensors, such as the number and type of channels, measuring ranges and value limits. An increase in student interest and motivation to learn STEM has been constantly observed through the direct interaction with a variety of devices they purposely integrate into their own designed and conducted applications. Consequently, they emphasis the advantage of the DMSRP over the commercial systems such as CASSY [10] or PASCO [11] for carrying out experiments in physics, where the students work with sensors embedded in the "Black Boxes", about which they have no knowledge of the sensors' characteristics or function principle. Moreover, features of sensors connected to the Raspberry Pi including programable modes to fine-tune the measuring process, on-board filter and amplifying circuits open ways to building new knowledge and to developing science and practice skills, in contrast to virtual laboratories applications that emulate the behaviour of real lab components. In addition, experimenting with real sensors connected to the DMSRP broaden students' learning of new STEM contents including the physical principles of operating sensors, the fundamentals of electronics and communication protocols, and the principles of digital signal processing techniques. Searching for the relevant parameters of sensors and putting them in equations to other physical quantities of the circuit and the instructions in the software configuration emphasizes the functional dimension of learning in an authentic contextualised environment. The capabilities of the DMSRP to provide immediate feedback by visualising the signal from sensors in real-time engage students in critical thinking on their preparatory actions, which leads to searching for more advanced experimental circuits for getting more accurate measurements enabling them to reach the desired quality in the functionality of the circuit as well as in the display and collection of measurement. Thus, students are challenged to explain why and how they act. On long-term, a coherent system of practical skills connected to the theory and to the purpose of application expands.

4. Exploring Interconnection of Science, Engineering, and Technology

The Digital Measurement System based on Raspberry Pi constitutes itself as a rich environment with a wide range of resources such as sensors and electrical components. Instructions that support and enhance students' performances can be organised as a chain of structured and iterative engineering design processes including planning, sequencing, managing and evaluating activities that connect theories, models and ideas to the methods of designing and generation of solutions. The DMSRP as instructional tool and learning resource is implemented in a contextualised environment supporting a continuous design-assessment-redesign cycle to reach the desired goal.

4.1 Identify and Explore Real-World Problem

Designing and conducting learning-centred instructions based on the DMSRP requires identifying and exploring science and technology problems from multiple perspectives through constructivist approaches such as inquiry-based, problem- and project- based learning. At the stage of exploring a problem to solve, STEM contents are contextualized to the particulars of the application to be explored with the DMSRP. To carry out measurements of specific quantities, students choose the appropriate sensors, analyse their characteristics based on the data sheet and look into their measuring principles. To measure and record quantities, students investigate the connectivity to the Raspberry Pi that is important for understanding data transfer. Thus, knowledge progresses through the principles of operating sensors, serial communication and data transmission to the Raspberry Pi in a learning environment in which theory and practice built upon each other. Students get an insight on doing science by combining knowledge, models, explanatory principles in various science, technical and mathematical representations across disciplines into an integrated conceptual framework. Educators organise instruction as collaborative activity and provide students with prompts, hints, models, summaries, especially in introductory phase or support them when encounter difficulties.

4.2 Planning and Carrying out Investigations

Activities based on inquiry, communication, construction, and knowledge representation are conducted at this stage to analyse the significant parameters of sensors and the ways to equate them to other physical quantities of the circuit. After having defined and investigated the science problem, students can then focus on how to reach the solution. They can then proceed to the design of the electric circuit, for which they need to know the functions and features of electronic components, as well as to understand how those components are to be connected on a circuit board. The practical realisation of the wiring diagram on the breadboard stimulates curiosity and motivation and engage students in multi-stage exploration involving trial and error, as well as the refinement of conceptual thinking. After the schematic and wiring diagrams have been realised, students have to configure the PhyPiDAQ software by choosing and editing specific configurations for the devices and sensors selected for their application. Logical reasoning is demanded to put the characteristic of the sensors, such as the number and type of channels, measuring ranges and value limits in relation to the built-in commands in the graphical user interface. The conceptual understanding evolves by gauging quantities such as voltage at some elements in the real circuit with respect to the characteristic of sensors or to the particularities of the built-in commands in the software. Students gain a higher motivation based on their personal contribution and mutual reliance as contributors to the community of practices [9]. The understanding and learning progress through sharing experience so that all participants reach at the end the desired learning outcome. In the long term, more cooperation across the learners leads to the occurrence of novel problematic issues, causing the development of conceptual understanding based on expansivity which is usually observed in learning in activity [12].

4.3 Conducting Measurements and Testing Results

At this stage, measurements are carried out. The data acquisition, display, and record start with the graphical user interface phypi.py of the software package PhyPiDAQ where the students have configured the sensors and the measuring process. During the experimental work, learner can optimize the visualisation of measurements by choosing proper graphical ranges and adapting the sampling rate of the measurement process. They also customize the visualisation of measurements by introducing title, or name and units for quantities. In addition, important feature of the DMSRP is its capability to introduce formulae to convert the output sensors' voltage into physical quantities, or to display desired dependencies of the measured signals. By carrying out complex tasks in this phase, students develop knowledge and deepen understanding in many interrelated STEM areas. DMSRP supports the progress of learning through activities in which students work on procedural and mathematical models, built their own representations of knowledge based on integrating of real experimental settings with visualisations and data processing. Therefore, large number of quality measurements that otherwise are difficult to collect in standard experimental settings are used to mathematically model the behaviour of the explored systems, such as growth or decay processes over a time period, by way of exponential functions. Based on the capability of the PhyPiDAQ software to save the data in .csv files, different features and dynamics can be analysed by means of spreadsheets like LibreOffice or Excel. Working out the collected data from real processes support the understanding of many mathematical structures, like sequences, function limits, numeric differentiation and integration methods and enable understanding of mutual relationships between physics concepts and laws and mathematical methods to model them.

4.4 Evaluating and Redesigning

The DMSRP enables students to constantly explore and assess the functionality and effectiveness of their own experimental setting even during the execution of the measurements. The visualization capabilities of the DMSRP provide feedback in real time and engage students in the iterative process to repeatedly improve the performances in their application. Critical thinking, analyse of evidence, and creative solutions are required for operating the circuits for the purpose of investigation, for troubleshooting the malfunction of the electric circuit or in the software, and for decision making to visualize, collect and process the measurements.

5. Case Study of Fraunhofer Diffraction: Investigating How the DMSRP Supports Engineering Design to Realise a Low-Cost Diffraction Scanner

Investigating the Fraunhofer diffraction based on the Raspberry Pi measurement system DMSRP is an example of integrating STEM contents and practices that complement and supplement each other in an authentic learning environment. From the teacher's perspective, the instructional design based on constructive learning theories has to incorporate activities meant to enhance students' knowledge, understanding and skills in the field of waves propagation and interaction with openings and obstacle.
The main goal of this instruction is the design of a low-cost diffraction scanner to measure the intensity of diffraction pattern instead of using the expensive commercial devices. The DMSRP should operate the scanner by reading the signal from a light sensor which has to be interfaced with the Raspberry Pi via an analog-to-digital converter. This is the driving question of a Project-Based-Learning strategy that engages learners in jointly solving an open-ended authentic problem through a chain of purposeful hands-on investigation, collaborative learning and technology-based exploration. Educators organise learner-centered and goal-oriented iterative instruction, guiding students to integrate scientific knowledge with design practices, and to specify criteria and constrains for the desired characteristic of the end-product. The starting point is to choose the suitable electronic component or sensor for scanning the diffraction patterns in terms of characteristics such as its easily integration into the measurement system, sensitivity, size, and dynamic performance. After searching and comparing the datasheets of various electronic components, students opted for a simple BPW34 photodiode with high radiant sensitivity priced at €0,70 [13]. By analysing its parameters, such as its voltage and power values, students observed that this silicon photodiode provides good measurements through the direct connection to an analog-to-digital converter ADS1115 without any need of an external operational amplifier. Its operating mode as high-speed photodetector permits a faultless recording of the intensity of diffraction fringes over the whole visible wavelength. To reach their solution, students go through an iterative process in which some stages, such as designing schematics and realising wiring diagrams on the breadboard, measuring quantities and comparing outputs, are repeated multiple times. The digitalised signal is visualised in real time and recorded by means of the PhyPiDAQ software on the Raspberry Pi. A first evaluation of the product along with the progress in students' knowledge take place at this stage. Based on the recorded results in individuals or group checklists, students present their solutions and obtain feedback from peers and teachers. By validation, they proceed to the next phase of the project aiming at embedding the BPW34 in an adequate black plastic case, chosen to meet criteria like utility and size. Carefully, the BPW34 photodiode has been mounted just behind a fine hand-cut entrance aperture. For experimental purpose the self-made diffraction scanner was fixed on a bolt that is clamped on a sliding rider. A built-in thumb screw allows for perpendicular movement to the optical axis of the available optics track, by means of a hand crank. With their low-cost diffraction scanner, students conduct measurements of the intensity of fringes in the Fraunhofer diffraction pattern, as shown in this video https://youtu.be/TDSzCIaUQVA . Each stage of this project-based-learning PBL to create the low-cost diffraction scanner provides context for new contents encompassing different Physics and Technology fields. The open-ended character of this PBL can drive the students to expand experimental work such as to apply the physical concepts to design new circuits to investigate how the photodiode works in the photovoltaic and photoconductive mode and apply their knowledge and skills to the broader real-world application of producing electricity based on photovoltaic cells.

6. Learning the Physics of Waves With the DMSRP

6.1 Employing Crosscutting Concepts to Understand Waves' Behaviour at Openings and Obstacles

Students work collaboratively to design, create and try out their self-made diffraction scanner based on a photodiode that generates voltage when the light of a laser illuminates it. Inquiry tasks guide students to explain the characteristics of the diffraction pattern obtained in the experiment when laser light falls onto a single-slit. Many students could not explain the occurrence of light and dark fringes because they expected to see a straight image of the aperture projected on the screen. This leads them to engage in answering deep questions with the purpose to explain why the idealised model of the light as straight ray as they applied for the propagation in optical systems is not applicable. A problem-based learning approach could involve students in searching ways to investigate this situation. As a result, a simple experiment in which students are asked to compare the effects produced by two different waves such as sound and light wave when passing through the open door into the dark classroom is setup to provide ground for dialog and argumentation. While the sound is heard everywhere in the room being diffracted at the door opening, the light creates a sharp image of the doorway on the floor, confirming the light representation as a ray. Therefore, they engage themselves in further investigation on under what conditions and for what purpose can light be modelled as ray or wave and what concepts, quantities and methods are required in each case. Crosscutting concepts [14] such as *Scale,* in this case the size of opening with respect to the wavelength, decides on whether the ray or the wave representation is appropriate. Moreover, the crosscutting concept of *Pattern* enhances students' ability to transfer knowledge from diffraction of sound or water waves to the new content of light and helps them to achieve more coherent understandings. Crosscutting concept of *Structure and Function* helps understanding diffraction at single-slit. Students employ their self-created diffraction scanner into the common experimental setting available in the lab and visualize the intensity of diffraction peaks on the measuring window of the DMSRP for various slit widths. This leads to their discovery that a decrease in the slit width results in an increase in the width of the central maximum, which is consistent to their prior observation of water waves in ripple tank, where the emergent wave from the gap in the narrowed barrier tends to form semi-circular shape.

6.2 DMSRP Supports the Investigation of Diffraction at Single-Slit and Interference at Double-Slit

This last observation is not enough to explain the diffraction pattern showing a bright central maximum followed by other maxima on either side. A certain similarity to the pattern created by double slits that students have already learned confirms the wave character of light. In their mathematical modelling process of interference from two slits, students have ignored first the diffraction effect in each slit and considered the two slits as two narrow point sources which radiate secondary spherical wavelets spreading out in the forward direction. By applying both Huygens' and superposition principles, the interference pattern with equally spaced maxima and minima has been explained. The DMSRP support students' investigation on the similarities and differences of the single and double-slit patterns. The real-time visualised diffraction pattern from a single-slit with the DMSRP shows a bright central maximum followed by a rapid decrease of the intensity of maxima on either side. This, however, differs from the pattern created by double slits with evenly spaced fringes with intensities slowly fading. While the human eye distinguishes with difficulties the differences in the shape and sharpness of the diffraction pattern on the screen, the DMSRP visualises and records at high accuracy the light intensity of the fringes versus position for various slits' geometries. Thereby, students correlate the diffraction pattern projected on the screen with the graph of the intensity of diffraction fringes on the measuring window of the DMSRP. The projection pattern is produced in real-time as students manipulated the hand-crank of the sliding rider. By choosing the *DataGraph*-Module in the configuration window, students obtain a real-time view through bar charts with which they could compare the intensity values. A more meaningful quantitative representation of the instant values of the light intensity is acquired by means of the Start/Stop command in the measuring window. Drawn from these values, students calculate the intensity of each maximum relative to the central maximum and quickly compare their output to the theoretical values from textbooks. Furthermore, students are engaged in contrastive learning approaches requiring them to recognize and explore the similarities and the differences between the two patterns as shown in the video https://youtu.be/JLmZB5XQdpg. As a result, students understand that the diffraction at single slit cannot be modelled with the interference of two secondary wavelets spread out from two-point sources. In addition, the learners are confronted with the similarity of the equation for destructive diffraction at single-slit and for constructive interference of two waves in the Young's experiment as provided by textbooks. To master these differences between experiments and textbooks, students engage themselves in complex procedure based on the superposition of wavelets generated by a uniform distribution of point sources at the slit.

6.3 Mathematics of Diffraction is Derived Through DMSRP-Based Learning Across Contents

By illuminating the slit with laser light, the DMSRP shows a bright central maximum followed by dimmer and thinner maxima on either side, which can be easily measured in the measuring window of the DMSRP. Students can be engaged in calculating the light intensity relative to the central maximum of an arbitrary point on the screen in the framework of a STEM based PBL. The driving question concerns creating of comprehensible mathematical model based on previously acquired structures, concept and tool to model the DMSRP visualised pattern. In this case, the model based on the phasor analysis has been often employed. Based on previously established experience and practices in modelling processes in alternating-current circuits, students build a logical progression of mathematical sequences to deduce the equations for diffraction orders as well as the relative intensities of light fringes. In their reasoning, students make use of the known practice to represent phasors, therefore the electric field of each wavelet is a phasor whose orientation is given by its phase state. Since the electric field vectors have the same amplitude and angular frequencies, and each successive component has the same phase shift relative the previous one, the phasors can be arranged in an arc of a circle. The total time-independent component of electric field at certain point on the screen is given by the magnitude of the phasor resulting from adding all the individual wavelets' contributions. To better represent the phasors' structure and to grasp important features and relationships, a dynamic representation of the phasors for different diffraction angles https://www.geogebra.org/m/Jd2VfGCH provides the learners with information about the geometry of phasors for maxima and minima in the diffraction pattern. By interconnecting computer simulation with the DMSRP visualisation, students construct a mathematical model to relate the phasor diagram with the intensity distribution of the single-slit pattern. The simulation shows that the amplitude of the resultant phasor reaches its maximum if the phasors are laid end to end in a straight line, whereas the minimum of intensity is reached when the phasors add to zero, after rotating through 2π one or more times. These representations match the equation from textbook. While the textbooks do not mention anything about the maxima of diffraction, students deduce the mathematical equation and justify why the intensity of maxima decreases as the diffraction scanner moves away from the central maximum. To calculate the intensity of the maxima, the learning is extended to the energy transported by electromagnetic waves, involving the crosscutting concept of *Energy*. Putting the intensity of light at an arbitrary point on the screen in relation to the time average of the square of the total electric field, students construct the function for the intensity distribution of the diffraction pattern and represent this dynamically https://www.geogebra.org/m/jx6cdgd7. Moreover, the measurements DMSRP stored in *.csv* file are analysed with spreadsheets to determine the ratio of the intensity of different maxima to the central maximum. The obtained values from real measurements show a very good agreement to the computed one from the constructed function. Also, the results from the DMSRP and the calculated function can be used to explore the effect of various slit widths at different wavelengths. This illustrates that the combination of DMSRP, spreadsheets and dynamic simulations support interconnected practices in the framework of integrated STEM contents and subjects. Now, students put side by side their calculated intensity distribution with the dynamic geometric simulation and with the DMSRP real-time visualisation, and engage themselves in deep learning through argumentation, exploration, evaluation and expansion to accommodate two actual wide slits separated by a certain distance.

6.4 DMSRP Supports Exploring of Interference in Two or More Actual Wide Slits Experiment

For two wide slits separated by a certain distance, the visualized light intensity distribution of the pattern with the DMSRP shows important changes. Students first make a hypothesis with an included diffraction pattern due to the individual slit into the interference pattern of the double-slit setting. By contrasting the visualized pattern in the window of the DMSRP to the known equation for constructive interference, students validate the same location of maxima but they notice a decrease in their intensity caused by diffraction effects. In a PBL, students investigate how the diffraction at individual slits influence the interference pattern as a whole. Consequently, they extend their mathematical modelling based on phasor diagrams to deduce the complex function that interrelates diffraction with interference and to iteratively verify their output with respect to the DMSRP real pattern. Students' mathematical reasoning progresses towards the construction of a function that is a product of two factors describing the interference and diffraction at the same time. To analyse the characteristics of this function, they can use the dynamical representation https://www.geogebra.org/m/dvh6bg3a to explore the effect of parameters for the ratio of slits' separation to the slit's width and for the number of slits. Based on the experiment outputs, students observe that the DMSRP visualised intensity distribution for three- and four-slit experimental arrangements coincide with the outputs of the simulated function of intensity, as shown in https://youtu.be/NA2ybLCOUIA. Inquiry tasks guide students to explain the effect of the diffraction factor in shaping the pattern. The DMSRP real-time visualisation interrelated to the simulated function and to the analyse of the recorded measurements with spreadsheets drive students toward the conclusion that the diffraction factor also limits the number of the interference peaks by causing the disappearance of some interference maxima if they have the same direction as diffraction minima. Students can extend their investigation to derive the mathematical condition for missing orders and contrast the result to the DMSRP visualised pattern for different numbers of slits with various widths.

7. Conclusions

The contribution of the DMSRP as technological tool and rich learning environment in STEM education has been discussed. Given the powerful computation capability of the Raspberry Pi and the opensource PhyPiDAQ software, the DMSRP manages acquisition, display, and storage of large amount of data from a wide range of inexpensive sensors that can be used in various content and context integrated STEM environments. Through constructivist approaches, students are engaged in solving open-ended authentic problems such as creating a self-made diffraction scanner to measure the intensity of a Fraunhofer diffraction pattern through a chain of purposeful hands-on investigation, collaborative learning and technology-based exploration. Engineering design as pedagogical approach is commonly employed in guiding students through the pathway of problem investigation, deciding on the necessary devices and sensors, designing schematic diagrams, building the real circuit, configuring the PhyPiDAQ software for the purpose of measurement, processing and analysing data, evaluating and communicating results. STEM contents within and across subjects are integrated in contextualised learning environments designed to support knowledge creation through crosscutting concepts and core ideas such as in the case of wave. The contribution of the DMSRP to model mathematically complex processes such as interference and diffraction by means of visualising the intensity of fringes in the diffraction pattern, as the students manipulate the self-made diffraction scanner is highlighted. The conceptual understanding in different STEM areas progresses through the direct interaction of students with components of real-circuits that they can choose with respect to the characteristic of sensors or to the particularities of the built-in commands in the software. Moreover, the critical thinking, argumentation and decision-making evolves based on the capabilities of the DMSRP to provide immediate feedback by visualising the signal from sensors in real-time, which engage students in continuously refining the experimental settings and measuring procedures. The role of mathematics as tool in data processing by means of spreadsheets has been overcome by the requirement to model mathematically science processed involving complex mathematical concepts and algorithms.

Collaborative inquiry and meaningful communication emphasise the social aspect of learning in the DMSRP based activities. Network tools allow students and educators to share information concerning sensors, schematics, wiring circuits on the breadboard, or collected data for modelling processes within the communities or on their own interest. Consequently, students become active contributors to their own learning in an environment which promotes self-confidence, endurance in learning complex concepts, excitement of solving authentic real-world problems and intrinsic motivation.

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