Innovative STEM Practices Fostering the Digital Transformation of Agriculture: The STEM4Agri Paradigm

Dimitrios Loukatos
Dept. of Natural Resources Management & Agricultural Engineering
Agricultural University of Athens
Athens, Greece
dlouka@aua.gr

Maria Kondoyanni
Dept. of Natural Resources Management & Agricultural Engineering
Agricultural University of Athens
Athens, Greece
mkondoyanni@aua.gr

Ioannis-Vasileios Kyrtopoulos
Dept. of Natural Resources Management & Agricultural Engineering
Agricultural University of Athens
Athens, Greece
kyrtopoulos@aua.gr

Dimitrios E. Kiriakos
Dept. of Business Administration, University of West Attica & DIEK Aigaleo
Athens, Greece
kiriakos@uniwa.gr

Yannis Psaromiligkos
Dept. of Business Administration, University of West Attica
Athens, Greece
yannis.psaromiligkos@uniwa.gr

Konstantinos G. Arvanitis
Dept. of Natural Resources Management & Agricultural Engineering
Agricultural University of Athens
Athens, Greece
karvan@aua.gr

***Abstract*—Recent advances in electronics industry resulted in numerous, amazing and cheap devices, while fluent documentation and efficient, user-friendly programming environments are available for them. Modern educational systems worldwide have exploited this dynamic by including in their didactic curricula practices reflecting this progress, under the STEM umbrella. Added to this, real-world problem solving techniques increase students' interest and prepare them for their future professional role. Such challenges and job opportunities intrinsically exist in agriculture, which is a critical sector for feeding the growing population on Earth, against natural source depletion and pandemics. In this context, this work explains how STEM – based techniques can be customized to form a characteristic bouquet of activities to better prepare students for their careers in a rapidly changing environment, resulting in an innovative skillset that makes agricultural practices more efficient and environmentally friendly. The suggested reinforcement of agricultural practices with high-end technologies would make them more successful. The paradigm being presented, with most of the focus on vocational education, has been developed and tested during the STEM4Agri Erasmus project. The positive feedback acquired from the participants, encourages the adoption of similar practices into the formal educational curricula.**

Keywords—Engineering education, Digital transformation, Multidisciplinary education, IoT, Smart Agriculture

I. Introduction

The rapid expansion of the electronics industry resulted in an era of diverse, affordable devices accompanied by comprehensive documentation and user-friendly programming environments. Capitalizing on this technological progress, modern educational systems globally have integrated these advancements into their educational curricula, fostering STEM (Science, Technology, Engineering, and Mathematics) practices. STEM, a widely recognized term in global education, underscores the imperative for a workforce proficient in STEM knowledge and skills to confront upcoming challenges [1]. This necessity aligns with the acknowledgment that adopting real-world problem-solving approaches not only boosts student engagement but also prepares them for future professional responsibilities [2-3].

In this regard, challenges for the humanity are not lacking, with the depletion of natural resources and the need for feeding the continuously growing population to be amongst the more imperative ones. Agriculture is one of the main sectors of primary industry that can provide solutions to these problems by embracing modern technologies. Indeed, according to FAO [4], the agricultural productivity should be increased by 60 per cent to tackle the abovementioned challenges, efficiently, by exploiting cutting-edge technologies, like electronics, robotics, IoT and AI. [5-6]. Augmenting agricultural practices with cutting-edge technologies stands to enhance the sector's efficacy in fulfilling its mission [6]. Well-educated personnel can drastically facilitate this mission and exploit the new job dynamics being created.

According to the definition of «21st century skills», a conceptual foundation is required to solve problems effectively, efficiently and with solutions that are reusable in different contexts [7]. The researchers indicate that 21st century skills can be categorized as: (i) ways of thinking, (ii) ways of working, (iii) tools for working and (iv) skills for living in the world [8]. Students should be well prepared for their professional careers, in a rapidly changing and demanding environment, and literally for jobs that are yet to be invented. Consequently, they should be ready for the digital transformation of the agricultural sector and the new jobs offered therein.

Despite the progress being done in secondary education the last decade involving STEM actions, in tertiary education many drawbacks should be tackled to meet the requirements previously mentioned, due to a variety of reasons starting from the increased complexity of the scientific subjects to be covered to the inefficacy of the educators to grow sufficient multidisciplinary capacities [9-10].

For the abovementioned reasons, this study endeavours to elucidate how STEM-based techniques, meticulously tailored to create a distinctive array of activities, can better prepare students of tertiary education for careers in a swiftly evolving landscape. By cultivating an innovative skillset, these techniques aim to render agricultural practices more efficient and environmentally sustainable. The underlying paradigm, focusing predominantly on vocational education, has been meticulously crafted and rigorously tested within the framework of the STEM4Agri ERASMUS EU project, grant agreement 2021-1-EL01-KA210-VET-000032913. This research aims to explore the customization and implementation of STEM principles within agricultural education, shedding light on the transformation of educational methodologies to prepare students for a dynamic and evolving professional domain. Through the insights gained from this study, the aim is to pave the way for a comprehensive, adaptable, and forward-thinking educational approach within the agricultural sector.

In order to better communicate the objectives of this work, apart from this introductory section, the rest of this paper is organized as follows: Section II presents the main methods and the materials being used. Section III provides interesting design and implementation details. Section IV is dedicated to evaluation results and discussion. Finally, Section V contains some important concluding remarks.

II. Methods and Materials

A. Project Framework

The activities described herein are mainly targeted to the acquisition of hands-on experiences [11] and of multidisciplinary skills toward a sustainable and profitable agriculture [12], involving cutting-edge technologies and improving the job finding prospects of the participants. In this regard, during the ERASMUS STEM4Agri EU funded project, people at the DIEK Aigaleo, the larger vocational institution of Greece, were encouraged to improve their knowledge about electronics, sensing and control, networking, programming, and physical process modelling, assisted by professors and students from the Agricultural University of Athens.

At a preparatory stage, educational material from the university lesson curriculum was modified and adapted to better fit the requirements of the vocational institution specialties program. Consequently, elements having practical and applied character were further highlighted, while pilot mechanisms were constructed to demonstrate functions of increased agricultural interest. Finally, the role of these pilot cases was communicated to persons acting as trainers at DIEK Aigaleo, through series of properly organized laboratory lessons. There was also provision for useful feedback from farmers and food chain experts from Greece and Cyprus, via a commercial partner specialized in this area.

At the main educational stage, people from the Agricultural University of Athens, assisted by trainers of the DIEK Aigaleo, orchestrated a selected set of scenarios during an educational program for the trainees at the DIEK Aigaleo. This program aims to assist persons, following specialties related to automatic control, computers, networks and programming, to improve their knowledge about technology itself and about the way that this can be applied for modernizing agricultural practices. The outcomes of this project will be used for the creation of a new vocational education specialty dedicated to digital agriculture.

The educational efforts were in accordance with the project based learning [13] and collaborative learning [14] methodology, while they draw inspiration from neighbouring field experiences, like the ones presented in [15-16]. Trainees were forming teams of 3-4 members, while discrete roles like hardware assembling, programming, measuring and testing, were assigned to the members of each team. Each member had to communicate his/her experiences to the rest of the team. The teams, preferably each week, had to complete a specific laboratory activity. In all cases, educators, apart from introducing the subject each week, were acting more as encouragers and consultants. The preparatory activities took place in 2022 while the main educational activities in 2023.

B. Pilot Case Paradigm

The educationally meaningful cases to be selected should be suitable for communicating the importance of many of the new and widely available technologies for modernizing the agricultural operations. Pilot scenarios should be of progressive but not high complexity and ideally should be completed by the participating trainees in two or four didactic hours, at maximum. Preferably, the outcome of each activity should be compact and demonstration-friendly. The most characteristic of the pilot scenario cases being formed are presented in the following bulleted list.

- Measuring soil moisture using an Arduino Uno board and sensors of different technology.
- On-Off control scenarios using relays soil moisture, gas and/or distance sensors.
- Phototropism imitation for maximizing the performance of small agrivoltaic systems, using photoresistors and angle servos.
- Controllable air/water flow using pulse width modulation (PWM) and proportional – integral – derivative (PID) techniques.
- Fruit and leaf classification according to their color, using a cheap RGB sensor module.
- Monitoring air temperature and humidity using NodeMCU nodes, a smart phone, and the Wi-Fi communication protocol.

The components being used are further discussed in Section C, while design and implementation details are given in Section III.

C. Component Selection

All the components involved in the discussed activities, both hardware and software ones, were selected so as to be easy-to-find, as free and of open design as possible, to have large supporting communities, to be as cost-effective as possible and to allow reusing them in different layouts. These arrangements resulted in educationally friendly and suitable for quite inexperienced programmers and crafters settings. Recyclable materials and parts from retired electromechanical equipment were also consisted a fine source enriching the potential component selection.

Amongst the useful components meeting most of the above specifications were:

- The Arduino Uno microcontroller board [17], with its robust and well-documented design.
- The cost-effective NodeMCU microcontroller board, based on the ESP8266 [18] chip offering, apart from Bluetooth connectivity, valuable Wi-Fi networking options.

- Simple and cheap sensors like potentiometers, photo resistors, air temperature and humidity sensors, soil moisture sensors, distance sensors, colour sensors.
- Simple actuators, apart of course from light emitting diodes (LEDs), were buzzers for sound triggers, traditional and solid state relays, motor drivers intercepting microcontroller pulses, angle servomotors, mini electric fans and pumps, retired water pumps and fans.
- The Arduino IDE [19] programming environment, as complemented by the ArduBlock tool [20] for easy graphical code assembling, an option very useful for beginners.
- The MIT App Inventor [21] tool was offering a flexible and well documented mobile application development environment that was perfectly paired with the IoT potential of the NodeMCU nodes, via suitable programming extensions [22].

The whole laboratory setup required a computer per each team for programming, inspecting, testing and in many cases, powering the pilot constructions being made. A typical laptop was more than enough for these purposes, while a more compact selection was the adoption of Raspberry Pi 4 [23] single board computers instead, as these units provide standard connectivity, interfacing, and visualization options and support all the aforementioned software tools.

III. Pilot Case Arrangement Details

This section highlights interesting details behind the most characteristic of the pilot scenario cases.

A. *Diverse Soil Moisture Measurements*

It is one of the simplest activities being implemented and its scope was to acquaint trainees with the digitization and the sensor calibration process, and to make them aware of the readings differences experiences between modules of different brand and technology. The corresponding hardware and software arrangements are shown in Fig. 1.

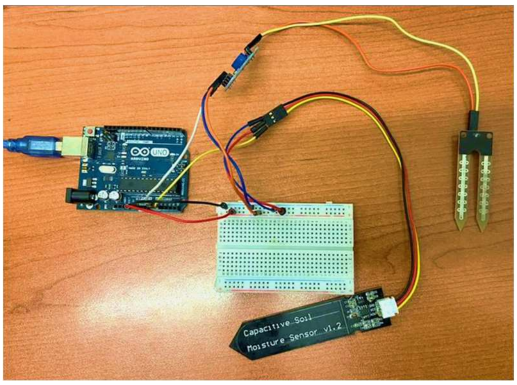

Fig. 1. Diverse soil moisture measurement arrangements utilizing cost effective sensing modules of resistive and of capacitive type

The 10-bit resolution built-in digitizer of the Arduino Uno board was utilized, along with the AnalogReadSerial basic example offered by the Arduino IDE environment, and its Serial Monitor and Serial Plotter visualization components, under the 'Tools' category. Alternatively the ArduBlock was used to compose the algorithm being necessary for reading and printing the sensor values. Despite its simplicity this pilot case had ice braking effect on the participants that were inspecting the moisture changes for different soil conditions, from completely dry to full wet ones, using a small pot with soil and a glass of water. The corresponding algorithm was also implemented using the ArduBlock visual environment, for comparison purposes.

The capacitive soil sensor had slower response to moisture level changes than the resistive one, but also exhibited better stability to changes of the soil salinity, which was modified by adding salt into the water, before putting it into the pot.

B. *On-Off Control Using Application-Specific Sensors*

In simple but not few agricultural automation cases sensing elements (e.g., for soil moisture or gas concentration or liquid level metering) can be combined with conventional relays in order to control a process (e.g., plant watering or farm ventilation or water tank filling). The microcontroller should then provide instructions to start or to stop the corresponding values after comparison of the sensor readings with the suitable threshold values. These values are defined empirically after in-situ measurements by the trainees. The necessary pairing software, for simplicity purposes, was implemented using the ArduBlock visual environment. The corresponding arrangements for the plant watering case shown in Fig. 2.

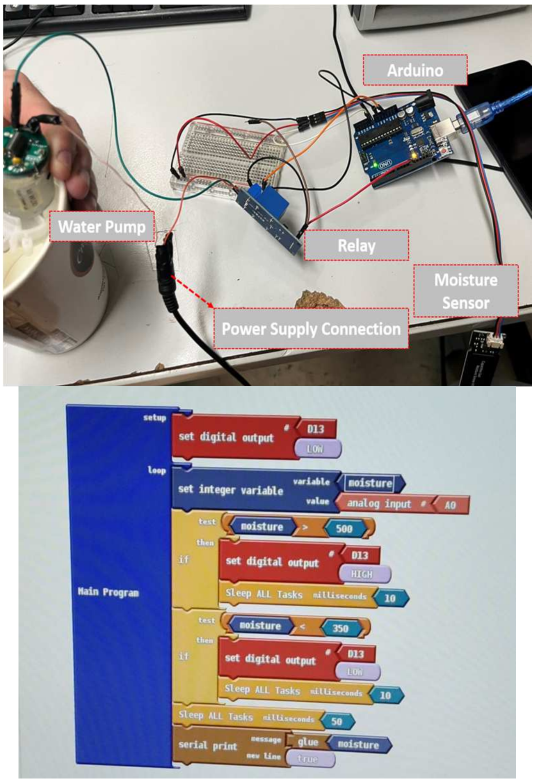

Fig. 2. On-Off control using soil a cheap soil moisture sensor module and a relay (top part) and the corresponding algorithm implementation using the ArduBlock tool (bottom part)

C. *Phototropism Imitation for Agrivoltaics*

The ability that plants have to direct their body toward the sun is exploited to implement a rotating platform able to host a small photovoltaic panel. This is the first scenario intending to familiarize trainees with control cases where progressive output is required instead of on/off type one. A small angle servo is utilized as the main action element, while to photoresistor based light sensors provide the necessary differential measurement guiding the servo. The systems rotates slightly to the left or to the right according to the result of the comparison of the 0.1 quantity with the normalized light intensity indication difference (ρ) provided by the metric:

$$\rho = (S_L - S_R) / (S_L + S_R) \quad (1)$$

More specifically, values for the ρ greater than 0.1 increase the angle servo output by 5 degrees, while values for the ρ smaller -0.1 decrease the angle by 5 degrees, with respect to the 0 and 180 degree limits. Values of ρ in between -0.1 and 0.1 do not cause angle changes. The pairing software, preferably, was implemented using the ArduBlock visual environment, giving life to the hardware components being interconnected, as shown in Fig. 3.

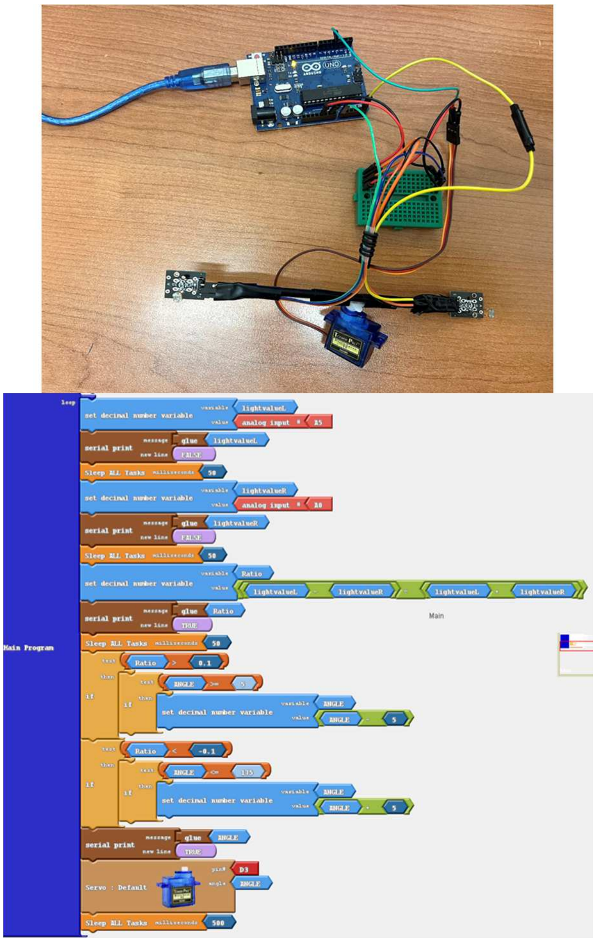

Fig. 3. A minimal chassis preparation for agrivoltaic panels utilizing two photoresistors and an angle servo (top part) and the corresponding algorithm implementation using the ArduBlock tool (bottom part)

D. Controllable Flow Using PWM Techniques

This is the second scenario intending to familiarize trainees with control cases where progressive output changes are required. The challenge in this case is to continuously follow a specific target flow value. The ability of the Arduino Uno microcontroller to provide pseudo-analogical output, via the PWM technique that generates rectangular pulses, is being exploited. The higher the duration ratio of the high state in the pulses, the faster the operation of the motor. Suitable motor drivers and external power supply are required as well. The actual flow value is measured directly by a suitable flow sensor, or, in case of air, indirectly by the measuring the displacement in centimeters of a piece of paper placed in front the electric fan. The latter option inspired the construction presented in Fig. 4 (top part). This activity scenario is actually a trimmed down version of the paradigm presented in [24] without the remote control part functionality.

The actual flow values (actually the corresponding distance of the piece of paper from an ultrasonic sensor) are compared with the target values and the differences are used to correct the current output. Toward this direction, simple PID controller variants were implemented on the Arduino Uno, as the one shown in Fig. 4 (bottom part), in order the system to keep pace with the target flow values provided by a potentiometer. The effect of diverse PID parameter settings was inspected by the trainees via the Serial Plotter component of the Arduino IDE. The corresponding software was implemented using the Arduino IDE textual environment.

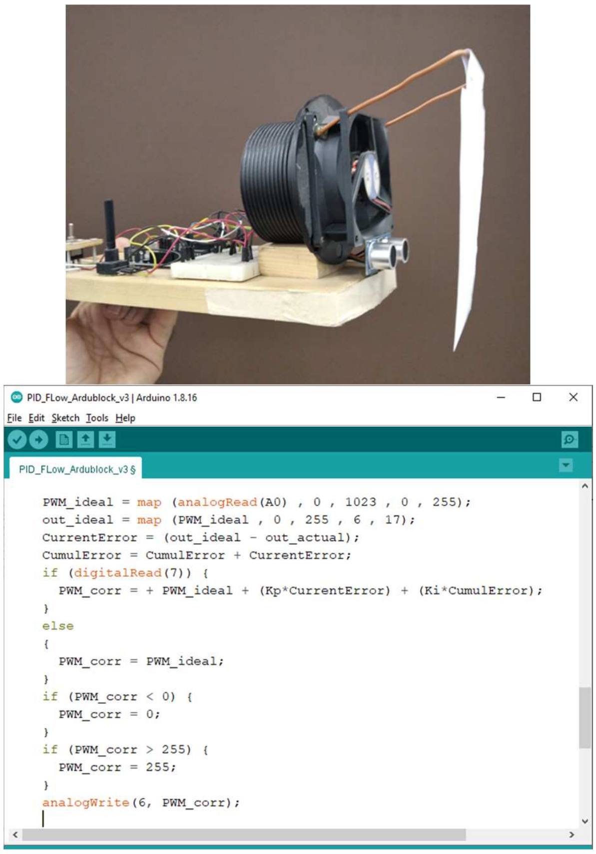

Fig. 4. Experimental controllable air flow unit utilizing the distance from a piece of paper in front of the fan as feedback parameter (top part) and an indicative implementation using the Arduino IDE (bottom part)

E. Fruit and Leaf Indentification Scenario

In food quality assessment or in plant disease detection, sensors combined with algorithms can provide valuable results. In this scenario case the Euclidean distance metric [25] has been used, applied in the 3-dimentional space of RGB colors, in order to identify fruit or leafs the one from the other. Specific types of fruits and leafs have been used as reference for comparison and their RGB coordinates have been used. For a specific sample under testing, the smallest among the Euclidean distance values calculated from the reference objects, is used for classifying properly. The corresponding hardware arrangements are shown in Fig. 5 (top part) involving an APDS-9960 colour sensor and an Arduino Uno. The corresponding software was implemented using the Arduino IDE textual environment, as depicted in Fig. 5 (bottom part).

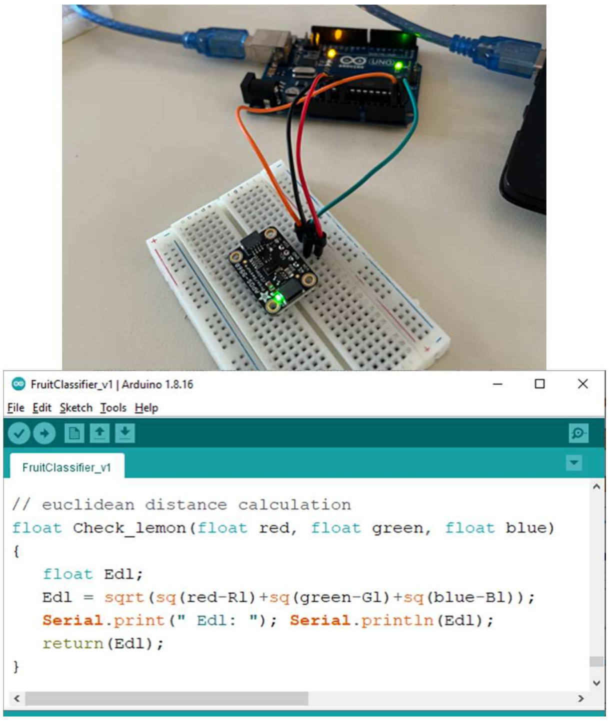

Fig. 5. An RGB color sensor as the key component for classifying objects, such as leafs or fruits, (top part) and the corresponding code part calculating the Euclidean distance metric (bottom part)

F. *Simple Wireless IoT Scenario*

As more experiences were gained by the participants, a simple wireless monitoring IoT scenario was implemented using a NodeMCU ESP8266 based board and an SHTC3 sensor. The later module, apart from being cost-effective is very fast and accurate for measuring air humidity and temperature. The corresponding IoT monitoring setup arrangements, involving a smart phone as well, are shown in Fig. 6.

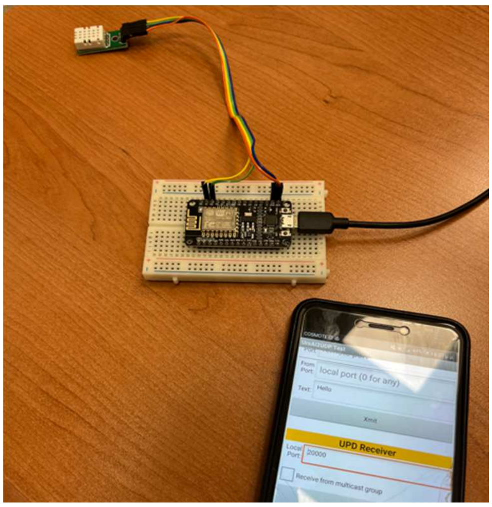

Fig. 6. Experimental IoT system for wireless monitoring of air temperature and humidity, via a smart phone

The code for the NodeMCU was implemented using the Arduino IDE textual environment, equipped with extra modules for supporting Wi-Fi and UDP functionality for the ESP8266 microcontroller family (e.g., the ESP8266WiFi and the WiFiUdp libraries). The pairing monitoring application, on the smart phone, was developed using the MIT App Inventor visual programming environment equipped with the proper extensions for simple UDP communication [22]. The most characteristic parts of the latter application are depicted in Fig. 7.

The interaction with the NodeMCU unit, apart from temperature and humidity periodical reports, also included serial packet number and signal strength information, for better communicating the IoT behavior fundamentals. For simplicity purposes, during the laboratory trials, both the NodeMCU and the smart phone were connected to the same access point, i.e., to the same WLAN.

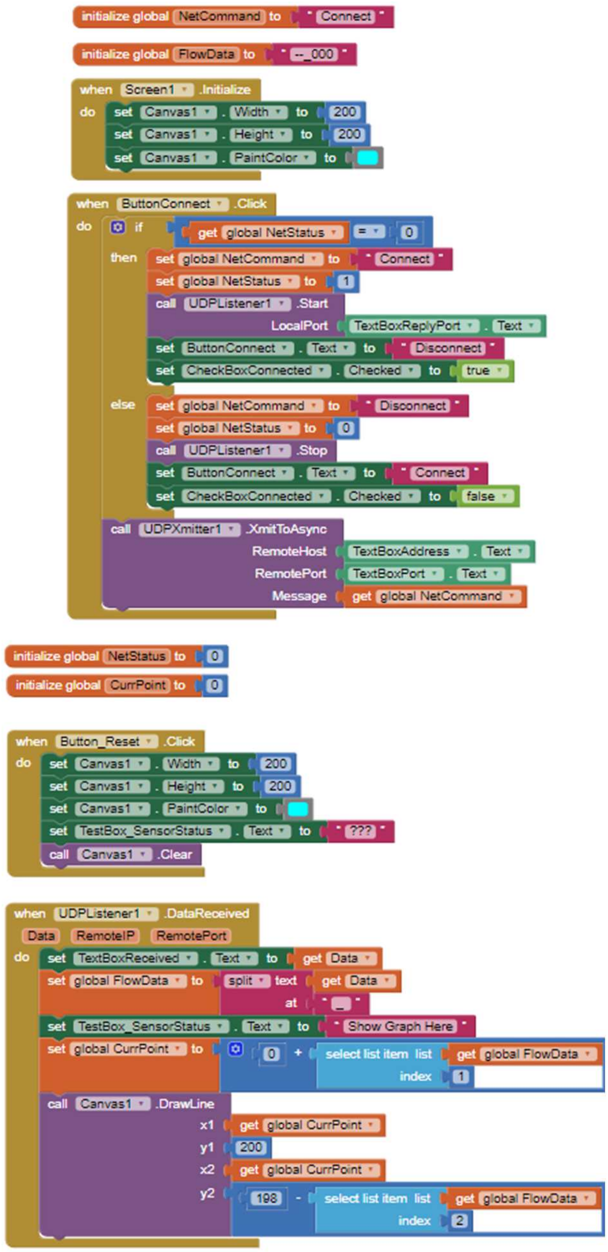

Fig. 7. The main parts of the IoT monitoring application for smart phones, as implemented using the MIT App Inventor visual programming environment

IV. Evaluation Results and Discussion

The proposed activities were assessed from different perspectives, both technical and educational, with most of the focus on the second ones.

A. *Brief Technical Assessment*

During the development of the assistive constructions being discussed, participants had to opportunity to test several different component setup arrangements exhibiting diverse performance and robustness. Quite often they had to redesign system or proceed to implementations with many components replaced with equivalent ones. Performance better than of 75% compared with the ideally expected was adequate for each activity. The intrinsic imperfections of the corresponding technical outcomes were acquainting the trainees with the idiosyncracies of a real-system, thus providing valuable learning opportunities.

The financial budget, supporting the proposed set of activities for each participating team, should provide 20€ for an Arduino Uno microcontroller board, 8€ for a NodeMCU board, 3€ and 10€ for the resistive and capacitive soil moisture sensors, 5€ for the air temperature and humidity sensor, 3€ for the ambient light sensors, 4€ for an RGB color sensor, 3€ for an ultrasonic distance sensor, 4€ for an angle servo, 5€ for a small DC motor and a liquid pump, 5€ to 25€ for motor driving and power supply equipment. The rest of the components could be covered by recycling/upcycling policy (i.e., utilizing retired AC motors and pumps or pieces of plastic and wood from protective packaging). The above analysis results in an overall cost estimated between 70€ and 90€. This amount is in line with the 'low-cost' character of the whole approach, especially considering the educational exploitation benefits and the component reusability potential of the proposed system.

B. *Educational Point of View*

The trainees participating in the STEM4Agri Erasmus program, were assisted to demystify technological practices applied in modern agriculture involving networking, physical process control, IoT, and system assembly. Pilot constructions were made summarizing the most characteristic functionality paradigm. To assess the effectiveness of the activities being offered, students were asked to complete preliminary questionnaires utilizing a five-point Likert scale [26]. This evaluation method is integral to the paradigm being presented, emphasizing the significance of these pilot-scale construction approaches aimed at enhancing agricultural efficiency while prioritizing environmental sustainability. Simultaneously, these activities seek to enhance students' understanding and perceptions of IoT (Internet of Things), automatic control, and system assembly—crucial subjects that hold considerable relevance for their future careers.

The survey being conducted aims to analyse the participants' views on the activities and involves 30 individuals who had previously taken part in the presented activities, each possessing varying degrees of experience, ranging from newcomers to STEM to those quite experienced in programming and electronic parts assembly. All the responders participated in this survey on a completely voluntary, confidential, and anonymous basis, aged from 18 to above 50 years old, with 12 from the total 30 persons being experienced in STEM issues and 18 being inexperienced. The data gathered were then processed using the techniques outlined in [27] and plotted as classic bar charts. The participation of the students in all the steps, from design to final implementation and testing, of the systems, created a meaningful learning environment encouraging the demystification of several high-end technologies that characterize modern agriculture and the modular nature of the systems being developed allowed for the elaboration of diverse tasks in parallel.

An indicative set of the early results being collected and processed is depicted in Fig. 8, Fig. 9, Fig. 10, Fig. 11, and Fig. 12. In all these figures, the height of each bar (vertical axis) expresses the absolute number of participants having a specific degree of agreement about the statement presented (sometimes shortened) depicted above the chart. The horizontal axis contains bar (opinion group) characterization, by a number from 1 to 5, where 1 means "Strongly Disagree", 2 means "Disagree", 3 means "Neither Agree or Disagree", 4 means "Agree", and 5 means "Strongly Agree".

In all cases, the setup remained as open and cost effective as possible, to maximize the reusability of components and to exhibit high modularity, thus allowing for several educationally meaningful checkpoints. More specifically, the survey results clearly indicate that the activities were beneficial to familiarizing the participants with the basic elements of the Internet of Things (IoT) (Fig. 8). Moreover, the respondents found that the proposed activities familiarized the participants with the basic elements of agricultural automation topics (Fig. 8). Similarly, participants' opinions about the cultivation of innovativeness were very positive (Fig. 9). The proposed activities also seem to enhance the professional prospects of the participants in the field of modern agriculture (Fig. 9), and that activities including similar topics and tasks should be incorporated in the official institute lessons' curriculum more drastically (Fig. 10).

It was also indicated that the material of the activities attended sufficiently covers the fundamental aspects of the technological transformation of agriculture (Fig. 10). Additionally, the proposed activities enhance the participants' soft skills, such as communication skills and teamwork abilities (Fig. 11), and improve also the ability to describe and solve real-world problems (Fig. 11). Finally, the equipment used exhibits significant similarity to that in a real-life unit (Fig. 12), and most of the participants would like to participate in larger-scale activities of a similar nature Fig. 12).

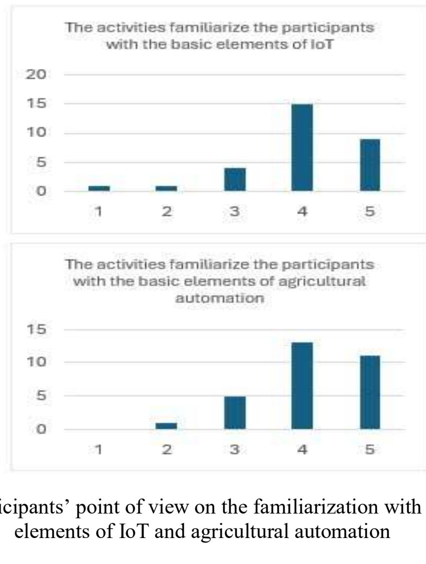

Fig. 8. Participants' point of view on the familiarization with the basic elements of IoT and agricultural automation

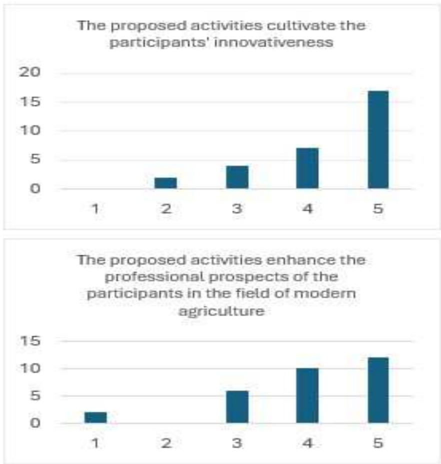

Fig. 9. Participants' point of view on the cultivation of participants' innovativeness and the benefits of the proposed activities for their career development in modern agriculture

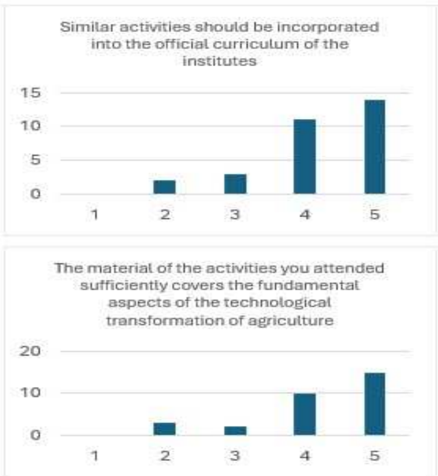

Fig. 10. Participants' point of view on the incorporation of similar activities into the institutional educational curricula and their opinion on the material to cover fundamental aspects of the technological transformation of agriculture

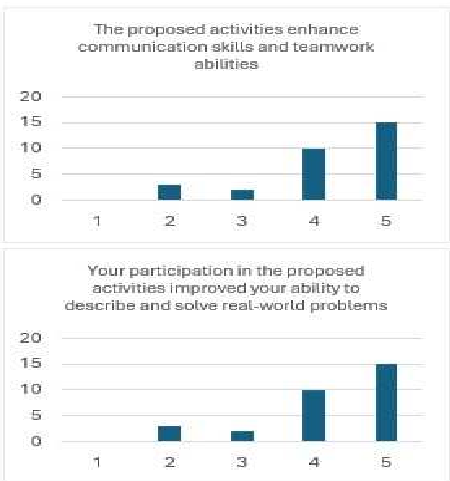

Fig. 11. Participants' opinion on the enhancement of communication skills, teamwork ability and the ability to solve real-world problems through the activities

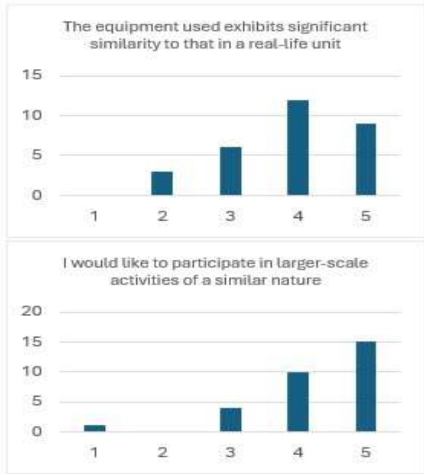

Fig. 12. Participants' opinion on the similarity of the equipment being used with a real-word production unit and their point of view on their participation in similar activities in the future

Table I includes the main statements used in the questions of the Likert survey, while means for each of them are shown in the rightmost column, to briefly summarize participants' opinions. Mean values close to 1 indicate low degree of agreement, while values close to 5 indicate high degree of agreement.

TABLE I. STATEMENTS USED TO MEASURE PARTICIPANTS' AGREEMENT

	Statement	***Mean***
1.	The activities familiarize the participants with the basic elements of the Internet of Things (IoT)	4.000
2.	The activities familiarize the participants with the basic elements of agricultural automation	4.133
3.	The proposed activities cultivate the participants' innovativeness	4.300
4.	The proposed activities enhance the professional prospects of the participants in the field of modern agriculture	4.000
5.	Similar activities should be incorporated into the official curriculum of the institutes	4.233
6.	The material of the activities you attended sufficiently covers the fundamental aspects of the technological transformation of agriculture	3.867
7.	The proposed activities enhance communication skills and teamwork abilities	4.233
8.	Your participation in the proposed activities improved your ability to describe and solve real-world problems	4.000
9.	The equipment used exhibits significant similarity to that in a real-life unit	3.900
10.	I would like to participate in larger-scale activities of a similar nature	4.267

C. Further Considerations

The proposed approach was tailored to better introduce to and communicate among the students the fundamentals of automatic control, a process which is of dominant importance for many processes of agricultural character and is also directly linked with other modern technological practices of the digital era, such as networking and sensing. It should be emphasized that, while there exist comparisons examining the impact of robotics in primary and secondary education, there's a scarcity of empirical research addressing the actual influence of implementing robotics in higher education [28]. These findings, as reported, align perfectly with and expand upon prior educational discoveries in this field [15,28,29]. Notably, upcoming professionals require competencies toward sustainable agriculture that embrace diversity and the integration of various knowledge, methods, and experiences, as well as the ability to respond and be proactive in a constantly changing world [12].

V. Conclusions

The plethora of innovative and low-cost electronics and of the accompanying software has been exploited to orchestrate indicative educationally meaningful STEM activities, at tertiary education level, focused on modernizing agricultural practices. According to a first set of survey findings, the paradigm being presented aims at highlighting the importance of such methods for making agriculture more efficient and environmentally friendly and, in parallel, improves students' perceptions related with IoT, automatic control and system assembly topics, which are of high importance for their future careers. The pilot constructions being created, in scaled-up versions, can be used to make the digital transformation of agriculture a process more understandable and feasible, while participants in the Erasmus STEM4Agri program became more suitable for supporting such objectives as process a future professionals. Finally, it is worth noting that the paradigm being presented can be seen as a source of guidance and inspiration for activities that should be incorporated into the curricula of educational institutes, as response to the modern technological skill demands and the forthcoming job transformation necessities.

Acknowledgment

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