APPROACH IN USING OPEN-SOURCE HARDWARE IN TEACHING SOLAR-POWERED IOT NODE DEVELOPMENT

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Abstract. *The rapid expansion of IoT and Smart city systems brings to our concern the questions such as powering numerous sensor nodes in those complex environments. Solar power emerges as one of sensor nodes' most interesting power sources. This fact allows us to think about the possible inclusion of topics such as the development of efficient solar-powered sensor nodes in the university curricula. Another motivating cause for this research is the proven efficiency of using open-source hardware in various university courses. This research combines the need for training engineers capable of designing energy-efficient solar-powered sensor nodes with the long-lasting and positive experience of utilizing open-hardware components in engineering education. First, this paper overviews different approaches to implementing open-source hardware, primary Arduino UNO, and clones in various lectures and topics within IT engineering education. These approaches are based on the personal experience of the author but also based on the experience of other researchers as well. After this overview, this paper analyses the possible courses where the inclusion of solar-powered sensor node development topics can be implemented. The Information Technology and Mechanical Engineering courses are the focus of this research. The proposal for the inclusion of the selected topics is made with a laboratory platform based on open-source hardware and software. This paper describes the platform and its components and analyzes what parts of the course syllabus can be covered with this platform.*

Key words: engineering education, Arduino UNO, solar-powered sensor networks, solar-powered sensor nodes development, energy efficient sensor devices.

Introduction

The rapid expansion of IoT and Smart city systems gives the motivation to think about the problems of powering numerous sensor nodes in complex environments. Solar power emerges as one of sensor nodes' most interesting power sources, considering its renewability. This conclusion makes us consider the challenges of the possible inclusion of lectures about developing efficient solar-powered sensor devices in the university curricula. Another motivating factor for the work presented in this paper is the proven efficiency of using open-source hardware in various university courses. Over time, Arduino has become ubiquitous in schools and universities worldwide [1]. This low-cost open-source device has changed how students, DIY enthusiasts, and STEM instructors can experiment with and learn to build various models and systems. This process is facilitated with repositories of online Arduino projects available at sites such as Instructables.com, and GitHub. The communities of learners and teachers are growing because of the Creative Commons licenses, and in that way, Arduino has allowed the democratization of engineering education.

This research combines and compiles the need for training engineers capable of designing energy-efficient solar-powered sensor nodes with the long-lasting and positive experience of utilizing open-hardware components in engineering education. Thus at the same time, it gives an overview of experiences in different approaches in implementing open-source hardware (Arduino UNO and its clones in the majority) in various lectures and topics within IT engineering education. These approaches are based on the long-lasting author's personal experience and the experience of other researchers and students cooperating with the author.

The paper is structured as follows. After the short introduction and presentation of the motivation for this research, brief analyses of the popularity of Arduino in education-related publications are presented in the past decade. This Section is followed by a brief introduction to the open-source hardware movement and its principles, explaining why it is suitable for successful implementation in education. The following Section presents a quick overview of numerous examples of implementing Arduino in university curricula as a part of lab exercises, student projects, and platforms for bachelor and master theses. All presented projects are part of the author's personal experience. The next Section introduces how the Arduino-based learning platform can be implemented in university curricula in Information technology and Mechanical Engineering courses for teaching the development of energy-efficient solar-powered sensor devices and for experimentation of solar panel efficiency and its dependency on ambient factors.

Related work

The popularity of Arduino and clone development boards and their usage in education can be found in various publications such as [2]. In the various approaches to using Arduino in education, we can refer to the following. In the paper [3] authors introduced the development of small-sized experimental devices for control research and education, focusing on using open-source technologies such as Arduino and Processing. Arduino is described as a pronominal open-source hardware whose architecture, implementation, and other necessary resources are accessible to every user. Processing is defined as its software counterpart, which supports the rapid development of controller/interface programs with little expertise.

Another paper [4] describes the setup of a benchmark industry 4.0 plant on a lab scale using advanced and state-of-the-art technologies necessary for an industry 4.0 plant that uses various controllers used in industries and various micro-controllers. The educational advantages of having such a lab setup of an industry 4.0 plant at a University are also discussed in this paper. The system architecture uses as the master PLC a CX 8190 Beckhoff PLC and other controllers connected as slaves with MODBUS communication protocol. The microcontrollers are Arduino Uno, Arduino Mega, and Raspberry Pi.

The next paper [5] presents a vision for how the software tools used for learning physical computing can be redesigned to fit better the group work for students aged 14–16. Physical computing is described as creating a conversation between the physical and virtual worlds of the computer. In the paper, the term physical computing is used for an activity in which students define the behavior of interactive systems in physical space. Arduino is considered one of the most well-known platforms used in physical computing projects, broadly used in classrooms across the world, considering that from December 2020, the Arduino community included over 48 million users based on the IDE downloads data.

The paper [6] presents how to teach children digital literacy and design thinking at primary and secondary schools. The focus was on exploring the tools that may support children's learning in these domains. To reach the learning goals, the toolkit called the Spark! Box is used. The Spark! Box includes conductive ink, Snap4Arduino programming software, crafting materials, such as straws, cardboard, and paperclips, and Arduino tailored ‘Spark! Module’.

The paper [7] presents the development of a digital manufacturing training demonstrator called the PERFORM turbine demonstrator. This project includes four aspects of Industry 4.0: Internet of Things (IoT), Augmented Reality (AR), the digital twin, and additive manufacturing (3D printing). The project covers activities such as printing a polymer turbine and testing using an Arduino microcontroller (MKR WIFI 1010) and sensors to monitor the system’s variable pump speed and turbine speed, temperature, and humidity.

Arduino publications

This paper provides a short illustration of the Arduino platform’s popularity in educational applications with the number of published articles on Arduino and teaching-related learning topics. The popularity is depicted with the search of the ScienceDirect database. Similar to the paper [8] where empirical studies were reviewed on maker-based assessments in education. In that paper, the review is based on published and unpublished studies from a wide variety of online bibliographic databases: EBSCO (including ERIC), PsycINFO, Proquest, ScienceDirect, ACM Digital Library, Google Scholar, and key conferences such as ACM CHI Conference on Human Factors in Computing Systems (SIGCHI), Conference on Creativity and Fabrication in Education (Fablearn) and ACM Conference on Innovation and Technology in Computer Science Education (ITiCSE). The authors used three major maker-related terms to search articles: maker activity, maker movement, and maker space. The search keywords were such as “3D printing AND making”, “Arduino AND making”, “Scratch AND making”, “Lego AND making”, etc.

The keywords used for search in this paper are: “Arduino”, “Arduino AND STEM”, “Arduino AND IoT”, “Arduino AND Solar Power”, “Arduino AND Sensor Networks”, “Arduino AND Education”, “Arduino AND Learning”, “Arduino AND Teaching”, and “Arduino AND Engineering Education”. Although the search results show several papers starting from 1999, only the results beginning in 2011 are counted. This criterion is applied because Arduino UNO as a board was commercially launched in 2010. The growth of the published paper by year is presented in Fig. 1, and the number of articles by year and keywords is shown in Table I.

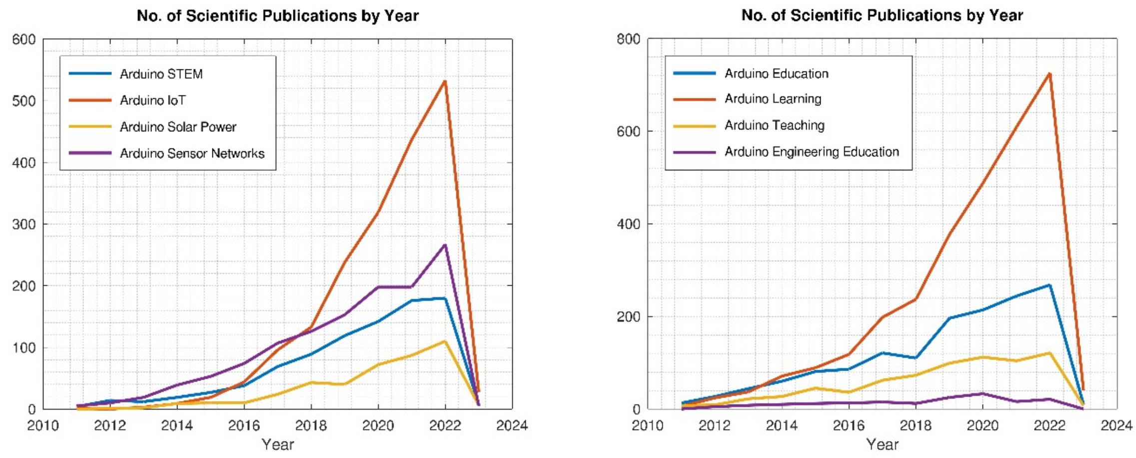

Figure 1. The number of scientific publications with Arduino-related topics in education since 2011

It is crucial to outline that the number of published articles is not decreasing at the end of the period, as seen in the picture, because some papers accepted for publishing are classified for the year 2023 before the start of that year.

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Arduino STEM	4	14	12	19	27	38	69	89	119	142	176	180	7
Arduino IoT	1	0	3	9	19	44	96	133	238	319	437	533	27
Arduino Solar Power	0	1	2	9	10	10	24	43	40	72	87	110	6
Arduino Sensor Networks	5	10	19	39	53	74	107	126	153	198	198	267	5
Arduino Education	13	27	44	60	81	86	121	110	196	214	244	268	10
Arduino Learning	6	24	37	71	89	118	198	237	377	488	609	726	40
Arduino Teaching	7	9	22	27	45	36	62	73	99	112	104	121	7
Arduino Engineering Education	0	5	8	10	12	13	15	12	25	33	16	21	0
Arduino	60	137	176	287	349	525	724	939	1190	1438	1696	1973	102

Table 1. The number of Arduino-related scientific papers in education since 2011

The last column gives the total number of papers with Arduino as a keyword.

Open-source hardware principles

The Arduino UNO and other development boards and clones have gained popularity because they are part of the open-source hardware movement. In brief, this movement is framed with the Open Source Hardware (OSHW) Statement of Principles 1.0. This statement states that "open source hardware is hardware whose design is made publicly available so anyone can study, modify, distribute, make, and sell the design or hardware based on that design. The hardware's source, the design from which it is made, is available in the preferred format for making modifications" (http://freedomdefinedorg/OSHW). This approach makes fertile ground for a broad community of developers, enthusiasts, and hobbyists willing to do projects and experiments and shares their experiences with others. Furthermore, to maximize the ability of individuals to make and use hardware, open-source hardware projects include available components and materials, standard processes, open infrastructure, available content, and open-source design tools.

With these foundations, the open-source hardware movement and its principles significantly facilitate the creation of low-cost and flexible platforms suitable for usage in university courses and academic research. These platforms are flexible enough to include various technologies to expand students' skills. The broad support from engineers, educators, hobbyists, and enthusiasts offers easy access to hardware design, software code, and project examples which, combined with low-cost and available hardware, fastens and empowers the process of its integration in education.

Some examples of platforms based on Arduino and its clones and their usage are described in the following Section. Arduino UNO is one of the most popular open-source hardware boards and is the basis of most presented projects.

Educational Arduino project examples

The selected Arduino-based projects from the author's experience are presented in this Section. The first example is given in Fig. 2. It started as a student seminar project and evolved into a research platform for testing and experimentation [9]. This project represents the wireless (Wi-Fi) sensor network with the MQTT protocol and Mosquitto broker support. The sensor network is designed for air quality monitoring and can be used in teaching as a prototype and test network for industrial environments [10].

The next platform was part of student lab exercises for the Computer Networking course and for teaching rapid development of IoT systems in a layered approach. This platform has layers, according to recent studies in the field. The students are involved in developing hardware prototypes using Arduino UNO Rev3 and low-cost sensors, software components using python to develop a UDP server, setup web proxy server configuration, and access to a cloud-based public IoT portal – ThingSpeak. During these tasks, students are involved in the development of all levels of small-scale IoT systems, such as (1) the processing layer, (2) the transport layer, (3) the middleware layer, and partially in (4) the application layer of a layered IoT system. The system is presented in Fig. 3 [11].

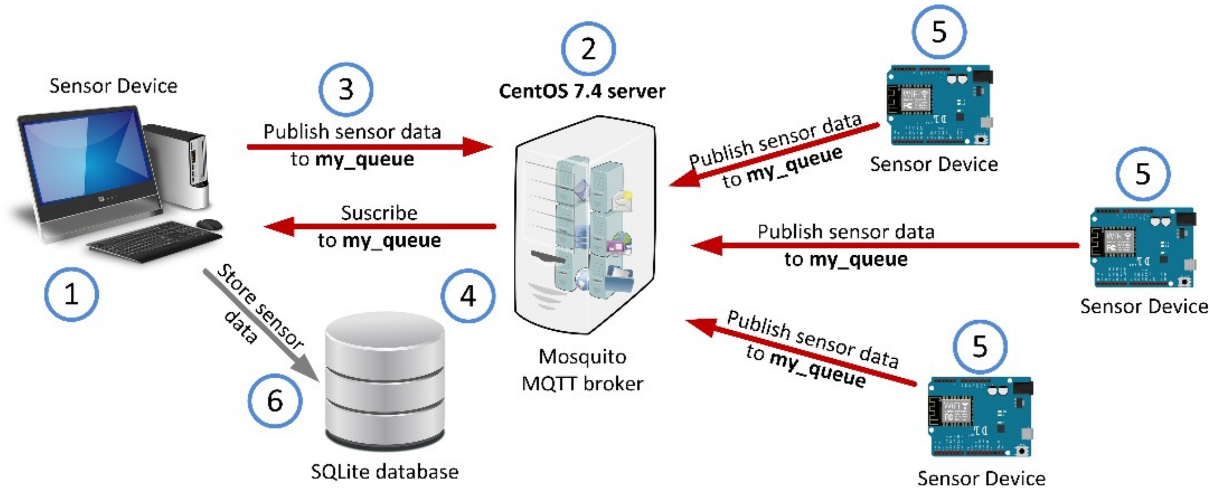

Figure 2. Wireless sensor network for air quality monitoring with the support of MQTT protocol

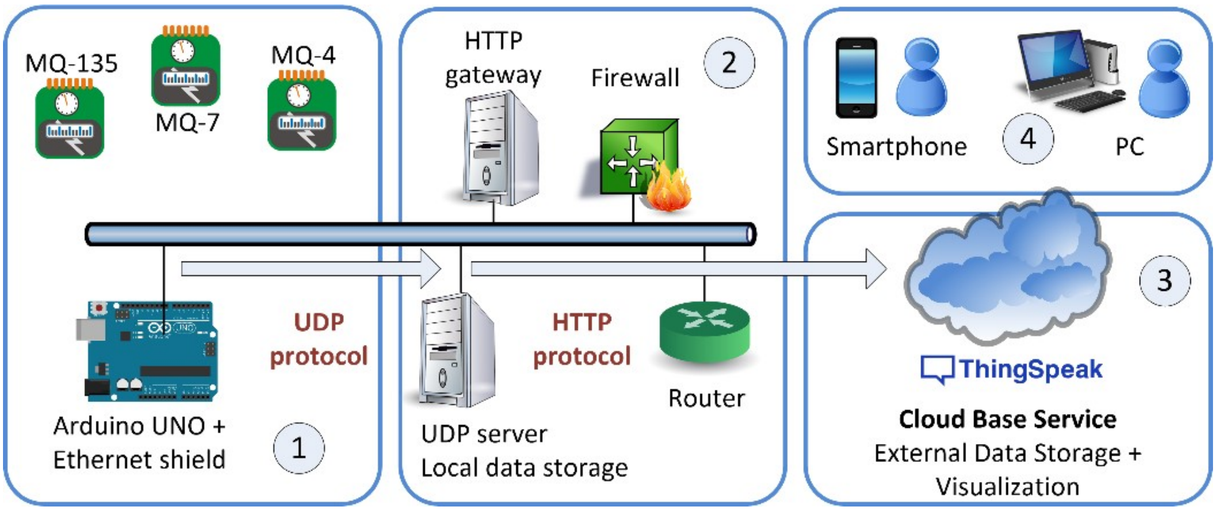

Figure 3. Small-scale layered IoT architecture

Fig. 4. presents the following example. It also started as a student seminar project, evolved into a bachelor thesis project, and was finalized as a significantly expanded master thesis project. The project uses NodeMCU ESP8266 sensor devices, Raspberry Pi 4, open-source Home Assistant software, and a cloud-based service for a small-scale watering system for home gardening with the possible expansion to larger coverage areas [12].

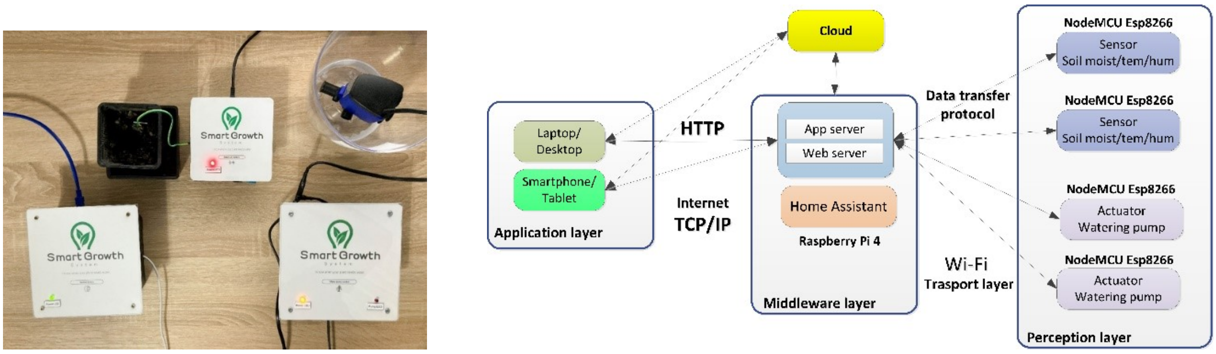

Figure 4. Open-source home gardening and watering system

The next part will briefly overview numerous examples of using Arduino-based platforms for teaching and academic research. The Arduino is used for developing temperature monitoring systems, both for student projects and academic research and experiment [13, 14]. The referenced works give various examples of using Arduino-based platforms to teach ZigBee [15], RFID [16], or combined technologies [17]. One example of using the Arduino platform in the design of a video surveillance system is in [18].

Additionally, the same university extensively uses these platforms for academic research and for measuring different wireless technology performances in indoor environments [19, 20, 21, 22] and outdoor environments [23, 24] and for indoor positioning systems (IDS) [25]. Moreover, these platforms are extensively used at the same university for academic research and for measuring different wireless technology performances in indoor environments [19, 20, 21, 22] and outdoor environments [23, 24] and for indoor positioning systems (IDS) [25].

Implementation of Arduino-based platform in teaching development and design of solar-powered sensor nodes

This Section will present the possible implementation of Arduino-based learning and research platform for developing solar-powered sensor devices and collecting solar radiation data. Once again, the main pillars of this platform are open-source hardware (OSHW) and open-source software components. Those components are used to achieve the following goals:

- Teaching platform to be used in IT courses, such as IT Engineering and Software Engineering, for the development of energy-efficient solar-powered sensor nodes,

- Teaching platform to be used in Mechanical engineering courses to analyze solar panel behavior, its efficiency, and dependency on various ambient conditions.
- The platform for scientific research on solar radiation data acquisition and analyses. Implementation of lab exercises in IT engineering and Software engineering courses.

The possible implementation of the described platform can be made in the following IT profile subjects:

- Communication systems (undergraduate),
- Computer communications and networks (undergraduate),
- Internet of Things (undergraduate), and
- Advanced Communication Systems (master).

A similar platform is planned to be included in the following Mechanical engineering courses:

- Energetics (undergraduate),
- Renewable energy sources (undergraduate),
- Energy efficiency (master).

In the current phase, laboratory exercises are implemented in the IT curricula for IT and software engineers. This set of lab exercises is built upon the Wemos D1 R2 and NodeMCU ESP8266 Arduino clones with integrated ESP8266 chip and Wi-Fi communication module. The ESP8266 is intentionally used to enable the development of solar-powered wireless sensor devices. The following exercises are currently in use:

- Wireless sensor node programming (simple LED web server controller),
- Simple Wi-Fi network scanner,
- Wireless sensor node programming with one analog sensor (photo and gas sensor),
- Wireless sensor node programming with digital temperature and humidity sensor (DHT-11),
- Wireless sensor node programming with I2C sensor (BH1750 light sensor),

- ESP8266 Wi-Fi communication, operational modes, IP, TCP, and UDP data connectivity,
- Energy efficiency, sleep modes, data acquisition protocol (data acquisition rate), wireless communication optimization, and duration of operational modes,
- Wireless solar-powered sensor node behavior (solar panel efficiency, solar charger management, Li-Po battery behavior).

Up to this date, these lab exercises are in practical use. The expansion of the lab exercises is planned with more advanced ESP32-based development boards. Fig. 5. shows the one form of the platform used for the lab mentioned above exercises and for academic research.

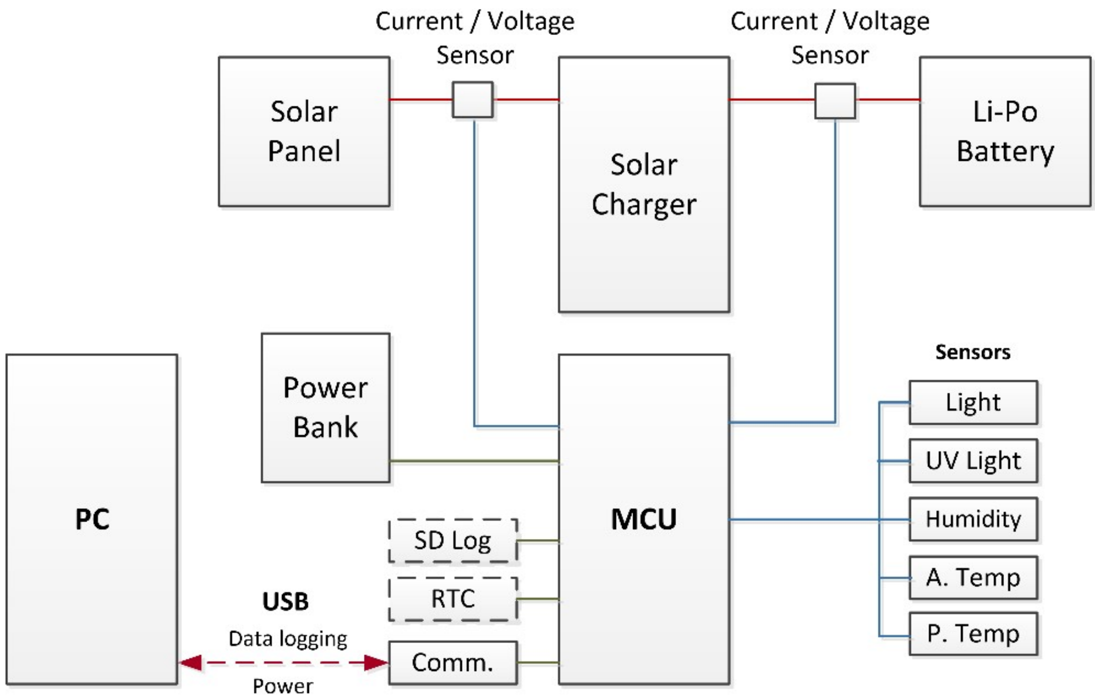

Figure 5. One variant of the platform for the research and development of solar-powered sensor devices

Conclusion

Broad experience in implementing open-source hardware in IT engineers' education is positive. The open-source hardware was successfully used during the long period for lab exercises, student projects, and seminar works, as well as for bachelor and master theses and academic research at our institution. With these platforms, students could participate in building WSN and IoT scenarios from the start in all phases of development. With this approach, students participated in all stages, from node creation and configuration, network setting, and node programming, to application development. This approach allowed students to have hands-on experience with emerging technologies during the lab exercises, compared to when they could only learn similar technologies using simulation software. With the positive experience, the expected results from implementing open-source hardware in solar energy-related topics in IT, Software, and Mechanical engineering education are as follows:

- similar hands-on experience,
- a deeper understanding of solar energy,
- a deeper understanding of energy-efficient sensor device design, development, and programming,
- multidisciplinary knowledge, and
- larger set and more interesting lab exercises.

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References

[1] A. Fidai, M. Capraro, R. Capraro, "Scratch"-ing computational thinking with Arduino: A meta-analysis, *Thinking Skills and Creativity*, Vol. 38, 2020, 100726, `https://doi.org/10.1016/j.tsc.2020.100726`.

[2] H. Kondaveeti, N. Kumaravelu, S. Vanambathina, S. Mathe, S. Vappangi, A systematic literature review on prototyping with Arduino: Applications, challenges, advantages, and limitations, *Computer Science Review*, Vol. 40, 2021, 100364, `https://doi.org/10.1016/j.cosrev.2021.100364`.

[3] M. Ishikawa, I. Maruta, Rapid Prototyping for Control Education using Arduino and Open-Source Technologies, *IFAC Proceedings Vol-*

umes, Vol. 42, Issue 24, 2010, 317–321, https://doi.org/10.3182/20091021-3-JP-2009.00060.

[4] J. Krushnan, F. Schödel, Development of a Modern, Low Cost, Lab Scale Industry 4.0 Plant for Education, *IFAC-PapersOnLine*, Vol. 55, Issue 17, 2022, 156–161, https://doi.org/10.1016/j.ifacol.2022.09.273.

[5] G. Roumen, Y. Fernaeus, Envisioning Arduino Action: A collaborative tool for physical computing in educational settings, *International Journal of Child-Computer Interaction*, Vol. 29, 2021, 100277, https://doi.org/10.1016/j.ijcci.2021.100277.

[6] T. Bekker, S. Bakker, I. Douma, J. van der Poel, K. Scheltenaar, Teaching children digital literacy through design-based learning with digital toolkits in schools, *International Journal of Child-Computer Interaction*, Vol. 5, 2015, 29–38, https://doi.org/10.1016/j.ijcci.2015.12.001.

[7] S. Keaveney, L. Athanasopoulou, V. Siatras, P. Stavropoulos, D. Mourtzis, D. P. Dowling, Development and Implementation of a Digital Manufacturing Demonstrator for Engineering Education, *Procedia CIRP*, Vol. 104, 2021, 1674–1679, https://doi.org/10.1016/j.procir.2021.11.282.

[8] Q. Lin, Y. Yin, X. Tang, R. Hadad, X. Zhai, Assessing learning in technology-rich maker activities: A systematic review of empirical research, *Computers & Education*, Vol. 157, 2020, 103944, https://doi.org/10.1016/j.compedu.2020.103944.

[9] D. Dobrilovic, M. Malić, D. Malić, Learning Platform for Smart City Application Development, *INDECS*, Vol. 17 No. 3-B, 430–437, 2019, DOI10.7906/indecs.17.3.

[10] D. Dobrilovic, V. Brtka, Z. Stojanov, G. Jotanovic, D. Perakovic, G. Jausevac, A Model for Working Environment Monitoring in Smart Manufacturing, *Applied Sciences*, 2021, 11(6):2850, https://doi.org/10.3390/app11062850.

[11] D. Dobrilovic, S. Zeljko, Design of an open-source platform for introducing Internet of Things in university curricula, Proc. of *2016 IEEE 11th International Symposium on Applied Computational Intelligence and Informatics (SACI)*, 2016, 273–276, doi:10.1109/SACI.2016.7507384.

[12] S. Felbab, D. Dobrilović, Z. Čović, J. Simon, Designing the prototype

of a scalable smart gardening system for testing and evaluation, Proc. of *11th International Conference on Applied Information and Internet Technologies – AIIT 2021*, October 15th, 2021, Zrenjanin, Serbia.

[13] D. Dobrilović, Ž. Stojanov, Z. Čović, J. Simon, N. Petrov, Model of data center temperature monitoring system with the use of open source hardware, Proc. of *2016 IEEE 14th International Symposium on Intelligent Systems and Informatics (SISY)*, 2016, 221–226, doi: 10.1109/SISY.2016.7601501.

[14] D. Dobrilovic, B. Odadzic, Z. Stojanov, V. Sinik, Testing Zigbee RF module applicability for usage in temperature monitoring systems, Proc. of *22nd Telecommunications Forum Telfor (TELFOR)*, 2014, 415–418, doi:10.1109/TELFOR.2014.7034436.

[15] D. Dobrilovic, Z. Stojanov, B. Odadzic, Teaching application development for RFID/ZigBee networks using open source hardware, Proc. of *X International Symposium on Telecommunications (BIHTEL)*, 2014, 1–6, doi:10.1109/BIHTEL.2014.6987641.

[16] D. Dobrilovic, Z. Stojanov, V. Brtka, Z. Čović, N. Bilinac, Software application for analyzing ZigBee network performance in university courses, Proc. of *IEEE 12th International Symposium on Intelligent Systems and Informatics (SISY)*, 2014, 73–77, doi:10.1109/SISY.2014.6923560.

[17] D. Dobrilovic, Z. Stojanov, B. Odadzic, V. Sinik, Platform for teaching communication systems based on open-source hardware, Proc. of *IEEE Global Engineering Education Conference (EDUCON)*, 2015, 737–741, doi:10.1109/EDUCON.2015.7096051.

[18] M. Malić, D. Dobrilović, I. Petrov, Example of IoT platform usage for wireless video surveillance with support of NoSQL and cloud systems, *International Conference on Applied Internet and Information Technologies ICAIIT*, Zrenjanin, Serbia, 2016.

[19] D. Dobrilovic, Z. Stojanov, J. Stojanov, M. Malic, Tools for modelling distance estimation based on RSSI, Proc. of *2nd International Workshop on Information, Computation, and Control Systems for Distributed Environments (ICCS-DE 2020)*, July 6–7, 2020, 43–52, Irkutsk, Russia, CEUR Workshop Proceedings, 2638, 265–276.

[20] D. Dobrilovic, B. Odazic, Z. Stojanov, Site-general indoor loss propagation model adjustment for 868 MHz RF modules, *Scientific Bulletin of The "Politehnica" University of Timişoara, Transactions on Auto-*

matic Control and Computer Science, Vol. 61 (75), No. 1, 65–72. ISSN: 1224-600X. 2016.

[21] D. Dobrilovic, B. Odadzic, Z. Stojanov, Approach in planning the deployment of 868 MHz RF modules in WSN scenarios, Proc. of *IEEE 10th Jubilee International Symposium on Applied Computational Intelligence and Informatics*, Timisoara, 2015, 387–392, `doi: 10.1109/SACI.2015.7208235`

[22] D. Dobrilovic, Z. Stojanov, J. Stojanov, M. Malic, Applicability of Michaelis–Menten model for signal strength estimation in wireless networks, *ICEST 2020 – 55th International Scientific Conference on Information, Communication and Energy Systems and Technologies*, 10th of September – 12th of September 2020.

[23] D. Dobrilović, M. Malić, D. Malić, S. Sladojević, Analyses and optimization of Lee propagation model for LoRa 868 Mhz network deployments In urban areas, *Journal of Engineering Management and Competitiveness (JEMC)*, Vol. 8, No. 2, 2018, 113–120.

[24] D. Dobrilović, Ž. Stojanov, M. Malić, D. Malić, Exploring the Performance of LoRaTM Modules for Indoor Based Wireless Sensor Networks, *Journal of Mechatronics, Automation and Identification Technology – JMAIT*, Vol. 3, Issue 1, 2018, 22–25.

[25] D. Dobrilović, D. Petrović, M. Malić, Usability of open-source hardware-based platform For Indoor Positioning Systems, *Journal of Engineering Management and Competitiveness (JEMC)*, Vol. 9, No. 2, 2019, 134–147.

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