Smart Eco Greenhouse VESNA

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Abstract: Recent challenges, including increasing global warming, reduction of carbon footprint, and limited resources of freshwater, enforce the implementation of smart solutions. This paper introduces the educational-oriented project VESNA (Versatile Simulator for Near-zero Emissions Agriculture, `https://vesna.uiam.sk`) focused on the development of a smart ecological greenhouse for micro-organic farming. This project provides an opportunity for students in the field of automation and control engineering to apply obtained theoretical knowledge and practical skills to monitor and control a real process. The prototype of the smart greenhouse is developed by the university students within the courses on both, bachelor's and master's levels. Moreover, the project emphasizes the soft-skills including teamwork, problem-solving, and presentation skills. Due to the COVID-19 pandemic, the students experienced a challenge to solve part of the project in a fully remote framework. The paper introduces detailed insight into the equipped hardware solution enabling both, autonomous and remote control of many controlled variables affecting the micro-climate inside the smart greenhouse. The educational goals, structure, and organization of the courses are also introduced. The detailed evaluation of the student's feedback on the proposed courses is analyzed to investigate the educational value and the benefits of the courses for the students.

Keywords: Control education using laboratory equipment; Balance issues of theoretical-versus-practical training; E-learning in control engineering

1. INTRODUCTION

Engineering education strives to provide balanced knowledge and skills in natural, technical, and technological sciences. As our society faces major environmental challenges in this century, it is becoming increasingly important to stress ecology, sustainability, minimization of resources, and waste management in the engineering curriculum. Our paper introduces smart eco greenhouse VESNA as a tool used in various courses at both bachelor's and master's levels in the study programs on cybernetics. The greenhouse is being built, maintained, and operated by students. It is a practical example of synergies between control, instrumentation, and environment.

The greenhouse is used in courses that concentrate on projects and teamwork. Several works investigate project-based learning (PBL). Cooperative learning is discussed in Johnson et al. (2014) to be distinguished from competitive or individualistic learning. Ruiz-Ortega et al. (2019) focus on project-led learning that results in lower student dropout rates and better soft skills. Beneroso and Robinson (2022); Gomez-del Rio and Rodriguez (2022) suggest that PBL promotes deeper interactions between students and educators and improves main student competencies. Student teamwork in software engineering is analyzed in Iacob and Faily (2019) to provide a better understanding of quality improvement. PBL in control engineering is discussed in O'Mahony (2008); Ignatyev et al. (2021). A recent survey in process system engineering education on PBL-based learning, active learning, group work, and real-world situations in Kondili et al. (2022); Lewin et al. (2022) strongly recommends student-centered active education.

The main contribution of this paper is to introduce the greenhouse, its principles, functionalities, and environmental and smart goals. We will discuss various innovative ideas in courses that use the device to help to make the study attractive to students. The goal is to improve not only students' technological, and engineering skills but also their soft skills, deepen their active learning, and make them sensitive to sustainability and environmental issues.

2. THE SPIRIT OF VESNA

Global climate changes significantly speed up the progress in sustainable production. Recent challenges, including increasing global warming, reduction of carbon footprint,

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and limited resources of freshwater, enforce the implementation of smart solutions. The goal of the project VESNA [1] is to design a smart eco greenhouse introducing recent technologies enabling smart, ecologic, and effective organic farming into modern food production. Therefore, the project VESNA is the next generation of smart eco greenhouses developed by open-minded young researchers and students.

VESNA was originally designed as an assignment for a student project, but it grew up into a complex project with a scope far beyond a term project. The project merges two essential principles of modern and sustainable food production—smart technologies and ecological approaches—into a unique ecosystem consisting of the greenhouse device itself, an effective communication interface, and advanced supervision driven by shared expert knowledge. We emphasize the environmental issues in the framework of the project to deepen the students' sensitivity to environmental issues. Therefore, the development of the project respects and supports essential principles of organic farming. Simultaneously, we strengthen the problem-solving approach of the students in the field of control engineering to carry out advanced and smart solutions leading to competitive advantages. The project also implements advanced self-awareness in autonomous decision-making, effective communication with the autonomous control unit and remote control, integration of external information and expert knowledge, minimization of the energy consumption necessary for heating/cooling and lighting, and optimization of the energy utilization necessary to run the control unit.

3. CONSTRUCTION

The current construction of the device is cuboid-shaped, composed of an aluminum frame, see Figure 1. The geometrical dimensions of the greenhouse device are: 0.5 m (width) × 0.5 m (length) × 1 m (height). The walls are made of custom-designed and laser-cut acrylic plates. To reinforce the construction, metal sheets have been used. All components are attached together by the custom-designed 3D printed parts. These parts, along with the acrylic plates and metal sheets, have been designed and modeled on FreeCAD software [2]. The doors are located on the front side of the construction, while fans and sensors are built-in on the right and left sides of the greenhouse. The microprocessor-based control units, as well as the power supply, are placed on the backside of the construction. The "intelligence" of the smart greenhouse, i.e., the autonomous and remote control is provided by the infrastructure consisting of the set of properly selected sensors, actuators, and microcontrollers summarized in detail below.

3.1 Sensors

The greenhouse is equipped with multiple sensors to measure inner temperature, humidity, light intensity, CO_2, and total volatile organic compounds (TVOC) (Table 1).

Fig. 1. Implementation of the smart greenhouse located at Slovak University of Technology in Bratislava.

Table 1. Overview of installed sensors.

#	Type	Measures	Signal
(1)	DS18b20	temperature	digital
(2)	BME680	temperature, humidity	I^2C
(3)	DHT21	temperature, humidity	digital
(4)	TEMT6000	light intensity	analog
(5)	MH-Z19b	CO_2	serial
(6)	SGP30	eCO_2, TVOC	I^2C
(7)	Si7021	temperature, humidity	I^2C

Two temperature sensors (Table 1, #1) are located at the very bottom and top of the greenhouse. Temperature and humidity are also measured by two sensors (Table 1, #2, #3) in the middle of the construction. Light intensity (Table 1, #4), CO_2 (Table 1, #5), and eCO_2, TVOC (Table 1, #6) sensors are mounted at the same height. The ambient temperature and humidity outside the greenhouse are also measured by a dedicated sensor (Table 1, #7).

3.2 Actuators

The greenhouse is equipped with several actuators (Table 2). The heater (Table 2, #1) and air-humidifier (Table 2, #2) are located at the bottom of the greenhouse. Fans (Table 2, #3) are provided to cool down the temperature and to deliver fresh air. The light intensity can be changed by GROW LED strips on the ceiling (Table 2, #4). All of the installed actuators provide signals using PWM communication.

Table 2. Overview of installed actuators.

#	Actuator	Components
(1)	Heater	HTS-14-24-40-3/4.8, heat sink, 12 VDC 40x40 fan.
(2)	Air-humidifier	Water tank, 12 VDC 120x120 fan.
(3)	Fans	109P0812M701.
(4)	Illumination	GROW LED strip.

3.3 Microcontrollers

Two microcontroller units (MCU) provide communication with the actuators and sensors, respectively (ESPRESSIF, ESP32-DevKitC-32D, WiFi, BlueTooth Low Energy, 4 MB, GPIO, I^2C, I^2S, SPI, UART). Both MCUs are equipped with WiFi modules and communicate with cloud services. Currently, the project VESNA utilizes an efficient data exchange using the API of the Arduino Cloud IoT [3]

[1] Simultaneously, *Vesna* is a goddess of Spring in early Slavic mythology.
[2] https://www.freecadweb.org
[3] https://docs.arduino.cc/arduino-cloud

service. The greenhouse communicates via WiFi with the separate control unit running the autonomous control evaluated by MATLAB [4] programming environment. Simultaneously, the web-based interface is able to override the autonomous control unit to provide remote supervision and control.

3.4 Irrigation unit

The separate irrigation unit provides optimal soil moisture in the flower pot placed in the greenhouse. It consists of a soil moisture sensor, a water tank, a pump, a flow meter, a liquid presence sensor, and a microprocessor platform (Table 3). The measurement from the soil moisture sensor (Table 3, #1) provides crucial information for the control unit to decide whether running the irrigation process is necessary. A non-contact sensor for the presence of liquid (Table 3, #2) is connected to the water tank. This sensor indicates whether there is enough water in the tank for watering. The retention tank is composed of an acrylic tube (100/96) mm. An ultrasonic sensor (Table 3, #3) is mounted at the top of the tank to measure the liquid level. Two pumps (Table 3, #4) draw water from the reservoir through the flow meter (Table 3, #5) and transport the water into the flower pot. The flow meter is used to detect the correct functioning of the pump. This entire closed circuit is controlled by the MCU decribed above.

Table 3. Components of the irrigation unit in the prototype of the smart greenhouse.

#	**Type**	**Hardware**
(1)	SEN0193	Soil moisture sensor
(2)	XKC-Y25-NPN	Liquid presence sensor
(3)	JSN-SR04T	Water level sensor
(4)	3-6 VDC, 120 l/h	Pump
(5)	YF-S201	Flow meter

4. EDUCATION

The students and young researchers are an integral part of the research and development of the project VESNA. The project is developed in an open-source fashion and we aim to share the ideas of the project to inspire young researchers, students, and their supervisors to come up with smart and innovative ideas. The project VESNA successfully took part in the education of students at our institute at both bachelor's and master's levels and in several projects- and team-based courses. The other significant benefit of the educational setup is that this student project considers long-term development. The main educational and upskilling objectives include improving theoretical knowledge in design for embedded hardware, sensors, actuators, network communication, cloud technologies, automation and process control, mathematical modeling, and advanced controller design. The project VESNA increases also the practical skills of the students, among others: implementation on the embedded hardware, programming, and software development, distributed version control systems, project documentation, and providing support. Finally, the benefit of this project is the development of soft skills, including mainly: research and development, critical thinking, teamwork, and meeting management. Achieving the educational goals is supported by a dedicated course at the LMS Moodle [5] platform, This course integrates also a module generating a GDPR compliance certificate for the course competition for students. Students benefit also from the VESNA homepage that has dedicated pages for the student projects [6]. Moreover, the developed open-source code is available at GitHub [7]. The development of project VESNA went in the autumn of 2021 into a fully remote fashion as a consequence of the COVID-19 pandemic. The above-listed e-learning and online support tools significantly helped students to face the challenging experience of teamwork in an online and remote framework.

The project VESNA was integrated into the education at our university into three selected courses: the master level course "Project on process control", and two courses at the bachelor's level, namely course "Team project", "Project on process control".

4.1 Project on process control

From 2021, the project VESNA takes part in the master course "Project on process control". The course is scheduled in the winter semester of the final program year. Therefore, the project supervisors support students in professional and personal development also by challenging the team members to propose fresh and novel solutions for the tasks and experiment with innovative approaches and using modern technologies. Each team is agile and self-organizing. The role of the team leader is to build a highly motivated and high-performing team.

The main goals of the student project are to establish sensor-actuator communication, to bring basic intelligence into this device, and to provide comfortable remote control of the greenhouse. Three teams are formed to address the main challenges of the project. Each team has 3-5 members including the team leader. In contrast to the other widely-used concepts of the students' projects based on the competitive setup between the teams, the project VESNA mimics the business-based environment. Therefore, it emphasizes the cooperation and interconnections between the teams and the responsibility of each team for the success of the whole project. Each team solves two sets of tasks: (i) *mandatory* tasks are necessary for the successful completion of the project, and (ii) *optional* tasks serve to upgrade the project and to improve the final grading of students. Each task assigns its task manager responsible for successful implementation. The three teams are: (i) Core Team, (ii) Smart Team, and (iii) App Team.

The main goal of the Core Team is to ensure effective communication by integrating an API into the data exchange between embedded hardware (microcontroller, sensors, actuators) and cloud service (via WiFi). The team mainly operates in development environments for embedded platforms (C/C++) and cloud communication technologies.

The main knowledge areas and skills developed in Core Team are embedded hardware and data processing, wireless communication, and API integration.

[4] https://www.mathworks.com

[5] `elearn.uiam.sk/course/view.php?id=173`

[6] `vesna.uiam.sk/index.php/project-on-process-control`

[7] `github.com/oravec-juraj/vesna`

We point out that the tasks of the teams are interconnected, therefore, the inter-team cooperation dependencies are: data exchange (Smart Team, App Team) and device diagnostic (Smart Team).

The Smart Team brings intelligence into the greenhouse. The main long-term goal of this team is to introduce self-awareness into autonomous decision-making without the necessity of manual external interventions. The team mainly operates in the prototyping programming environment (MATLAB) and handles communication technologies to exchange data with a cloud service (via WiFi and API). The majority of control tasks consider the design of On/Off and PID controls. The project on the advanced offset-free model predictive controller (MPC) for the inner temperature control is currently solved.

The main knowledge areas and skills developed in Smart Team are process control, controller design, and wireless communication.

Inter-team cooperation dependencies of Smart Team are data exchange (Core Team), device diagnostic (Core Team), control hierarchy (App Team), and database of plants (optional) (App Team).

The App Team provides comfortable remote control of the greenhouse. The application/web-based interface developed for mobile devices (smartphones and tablets) provides the supervising layer above the internal autonomous control of the greenhouse. The main long-term goal of this team is to develop a web interface, manage the access right of the user accounts, and visualize data in a user-friendly way. The team mainly operates in programming environments for mobile devices (HTML, Java) and cloud technologies. The remote supervision of the greenhouse device includes the manual control of actuators, diagnostics, and analysis of the current measurements from the sensors. The online video streaming and time-lapse features are under construction.

The main knowledge areas and skills developed in App Team are wireless communication, software development, and process control.

Inter-team cooperation dependencies of the App Team are data exchange (Core Team), control hierarchy (Smart Team), and database of plants (optional) (Smart Team).

The agenda of the project development is scheduled for a semester (13 weeks). Table 4 proposes a detailed schedule of the student project.

Table 4. Scheduling of the project development within a semester.

Week 1: Kick-off project meeting.
Week 1-3: Build project route map:

- brainstorming on project goals,
- headhunting for each team,
- brainstorming on task- and time management,
- survey on particular tasks,
- build the project route map.

Week 3: Initial stand-up:

- present project route map,
- select optional tasks,
- propose task management – milestones and goals,
- propose time management for each task,
- assign roles in each team,
- assign *task manager* for each task.

Week 3-8: Development of the project:

- consultations with supervisors and solving tasks.

Week 8: Mid-term project meeting:

- present milestones and goals for each task,
- present remaining tasks,
- present updated time management for each task,
- discuss corrections to the original plan.

Week 9-13: Further development of the project

- implement feedback from the mid-term project meeting,
- consultations with supervisors and solving tasks.

Week 13: Final project presentations

- present final results,
- discuss the vision of the future goals,
- pick-up the feedback from the leaders and the team members.

4.2 Vertical project

Compared to the course "Project on process control" for master students, the "Vertical project" integrates two project courses at the bachelor level. These courses are scheduled in summer semesters 4 and 6 and the first of them is the first control-based project in the study. The project follows the educational concepts of vertical studios (Barnes, 1993; Peterson and Tober, 2014) where mixed-level students are combined together into groups. Therefore, each student completes the project through the program twice, once as a junior and once as a senior member of the group. The project is enriched by introducing synergistic effects of younger students learning from their older peers and older students practicing their manager and soft skills.

The general setup of the VESNA project remains analogous to the one presented in Section 4.1. The students work with the same repository and code as the master students. But, of course, the complexity level is lowered, focusing more on introductory, exploratory concepts and tasks. The lecturers and the young researcher also benefit from supervising this student's project. Students familiar with the project in their bachelor's course bring innovative ideas into the development of the project in the master's course. Moreover, the student feedback from both courses is used to adjust the particular tasks and schedule in a timely manner, thereby creating optimal conditions for students' creative activities and enhancing their newly acquired knowledge and skills.

5. STUDENT FEEDBACK

In order to evaluate the usefulness of the implementation of the project for the development of students' knowledge and skills, a survey was evaluated. The evaluation was provided by 10 graduates of the "Project on process control" course in the winter semester of 2021, and 11 students who completed the "Vertical project" at the bachelor level in the summer semester of 2022. The surveys in both courses had two versions. The first version was intended for team leaders and consisted of a series of questions related to each team member. The aim was to

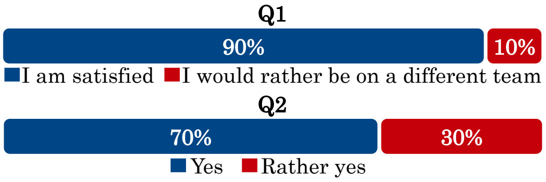

Fig. 2. Evaluation of master students' experience in the winter semester of 2021.

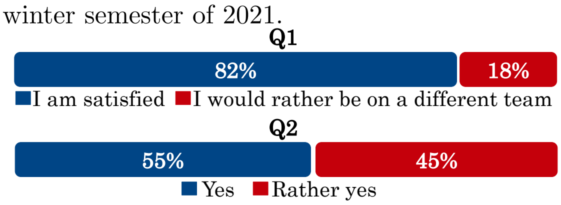

Fig. 3. Evaluation of bachelor students' experience in the summer semester of 2022.

evaluate the level of performance of tasks by individual team members and the approach to working in a team. In the next section, the team leaders had the opportunity to evaluate their team selection, their experience with the leadership position, and their overall satisfaction with the project. The second version of the survey was addressed to individual team members. These surveys were made up of 8 questions divided into two parts. In the first part, students had the opportunity to evaluate their managerial skills and ability to lead a team with their chosen team leader. The second part of the questionnaire was the same as the version for team leaders, i.e., the questions on overall satisfaction with the project. Questions were primarily formulated to simulate a real work environment where it is common practice to evaluate the soft and hard skills of colleagues in the team and/or the team leader in order to improve team cooperation. Questions for the team members, denoted by M1–M3, and the questions for the team leaders, denoted by L1–L3, are summarized in Table 5. Here, the purpose of the questions M4–M5 and L4–L5 (rated questions) was to make students evaluate their satisfaction with the crucial decisions and plans they prepared in the first weeks of the project. Answers obtained in the sections commented on above were also taken into consideration while grading. The last section of the survey, the questions denoted by Q1–Q3, was aimed to evaluate the benefits that the project brings to students. These questions are evaluated in more detail in the following Sections 5.1–5.2.

5.1 Feedback on the Project on process control

Answers to the master students' survey are evaluated in Figure 2. In Q1 students evaluate their satisfaction with their choice of the team they worked in. From the graph showing the result of Q1 in Figure 2, it is obvious that most of the students were satisfied with the chosen team. Based on this it can be assumed that the goals and tasks of teams were presented appropriately at the kick-off project meeting as students made their choices based on this information. Q2 serves to evaluate the benefits the project brings to students in terms of obtained knowledge and skills. In this question students could choose from 4 options: "*Yes*", "*Rather yes*", "*Rather no*", and "*No*". Since there are no negative answers, it is clear that the project met the students' expectations and helped them to develop new knowledge and skills. This is also evidenced by the students' answers to Q3. Some selected answers are listed below:

- "It was interesting to see how our work on sensors, communication, and actuators was reflected in the work of the Smart Team. It was a great feeling when we managed to turn on the LED lights through MATLAB."
- "I liked the idea of the project, to start a real system and apply our knowledge to it. I got a lot out of the project. Overall, I rate this project positively."
- "I was looking forward to the project as an opportunity to collaborate with my classmates on something tangible and new, the quality of which will depend on the integrity of all of us. I was curious how we would deal with it, what we would learn about each other, and whether it would give us more determination to look for a space for cooperation in the future. The project taught me a lot and I was interested in the fact that it was often things that I did not expect. The project brought me what I was looking forward to."

5.2 Feedback on the Vertical project

Answers to the bachelor students' survey are evaluated in Figure 3. Both graphs showing the percentage share of the answers to Q1 and Q2 indicate similar trends that we could see in Section 5.1. Even though answers to Q2 are more uncertain than in the previous section, there are also no negative answers, so we can summarize that the setup of the project is well planned to develop new practical skills and also to acquire new knowledge. This assumption is also supported by the answers of bachelor students to Q3:

- "Control of the real system and the possibility to see the difference in controller tuning in the simulation environment and the experiment in the greenhouse. What I enjoyed most about my work was that people saw the results of their work."

From obtained answers it is clear that students appreciate the opportunity to work in a team and also to cooperate between multiple teams:

- "Cooperation between all members of the project, getting closer to real work at a job."
- "Learning new things and working together."

6. COMMUNITY ENGAGEMENT

The project VESNA does not meet only the research and education goals. The project also aims to increase the control engineering community engagement. In this framework, from 2021, the prototype of smart greenhouse VESNA was an integral part of the numerous activities and events focused on promoting education in control engineering and science in general. Among other events [8], the VESNA was presented to thousands of in-person visitors of the "European Researchers' Night 2022" and "The Scientific Show 2022"—the flagship public-oriented events in

[8] Visit `vesna.uiam.sk/index.php/story` for the full list of events and links to the gallery of the pictures.

Table 5. The students' surveys.

Questions regarding evaluation of the team leader by team members:	
M1	How would you rate the quality of the team's leadership with regard to task completion and goal achievement?
M2	How would you rate the appropriateness of the time schedule and the consistency of its observance (time management)?
M3	How would you rate the communication and approach to teamwork?
M4	Are you satisfied with the choice of your team leader?
M5	Do you think the team leader had more responsibilities than you?
Questions regarding evaluation of the team members by team leaders:	
L1	How would you rate the quality and creativity of the solution to the assigned tasks?
L2	How would you rate the consistency of meeting the time schedule (time management)?
L3	How would you rate the communication and approach to teamwork?
L4	How satisfied are you with your team's composition?
L5	Would you agree to the position of team leader again?
Questions regarding evaluation of the project:	
Q1	Are you satisfied with the choice of your team or would you rather be in another team?
Q2	Did the project meet your expectations regarding your acquired knowledge and skills?
Q3	What interested you the most in the project?

Slovakia. A number of high school students with a high interest in science and technology enjoyed the remote control of the smart greenhouse and discussed the details of the project VESNA. Online, for interested readers, the project VESNA provides a homepage and shares the project highlights using a social media[9] labeled by "`#VESNA`". The project VESNA was also presented in a separate article in the popular public-oriented site "Science Within Reach" (in Slovak). Future goals include also an organization of the VESNA Hackathon[10] (makeathon).

7. CONCLUSIONS

After a year of intensive development, the project VESNA grew up into a long-term educational and research project driven by highly motivated students and young researchers. Currently, the students at the master's level continue in the project development and we expect new interesting extensions. Among other expected goals, is an introduction of remote visual surveillance as the platform for machine-learning-based evaluation of image recognition for advanced autonomous control and diagnostics. The supervisors benefit from the various original ideas and solutions proposed by students. Moreover, one of the coauthors of this paper already supervises a bachelor thesis focused on the designing of the advanced optimization-based data-driven controller design for the control of the greenhouse micro-climate.

The future extensions of the project in the upcoming summer semester of 2023 include the integration of renewable energy resources. The students will install a solar panel and integrate it into the energy supply of the smart greenhouse. Therefore, the project VESNA will introduce a new student team: a Solar Team focused also on smart grid optimization. Based on the gained experience, the future goals include the introduction of a new construction of the smart greenhouse. The new greenhouse has already been designed and the construction is under final development. Therefore, the upgraded construction is expected to be presented at the beginning of the winter semester of 2023.

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