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An international hands-on IoT education platform towards Industry 5.0

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ABSTRACT

This paper presents VREL NextGen, an international Internet of Things (IoT) education platform developed through European university collaboration. The platform addresses hands-on IoT education needs in the Industry 5.0 context through three distinct implementations: a microcontroller laboratory at the Silesian University of Technology, a building management sensor network at Riga Technical University, and a human-robot collaboration platform at Tallinn University of Technology. The system enables remote access to physical hardware while promoting resource sharing and standardized educational approaches. Implementation results demonstrate effective integration of theoretical knowledge with practical skills, supporting both fundamental engineering concepts and advanced IoT applications while emphasizing human-centric design principles of Industry 5.0.

1. Introduction

The evolution of industrial paradigms has witnessed a remarkable transformation from mechanization to digitalization and now towards human-centric intelligent manufacturing. Industry 4.0, characterized by the integration of cyber-physical systems and digital technologies, has laid the foundation for smart manufacturing through interconnected systems and data-driven decision-making. As we advance toward Industry 5.0, the focus shifts to creating synergy between human cognition and intelligent machines, emphasizing sustainability, resilience, and human-centricity in industrial processes (European Commission 2021; Özdemir and Hekim 2018). The Internet of Things (IoT) is a fundamental enabling technology for Industry 4.0, with its industrial variant (IIoT) becoming increasingly prevalent in the manufacturing sector. While new production systems inherently incorporate IoT functionality, a significant challenge lies in modernizing legacy equipment. Manufacturing machinery designed for operational lifespans spanning decades requires strategic IoT integration rather than wholesale replacement. This modernization through IIoT is crucial for adapting existing infrastructure to meet contemporary data-driven production demands, thereby enhancing operational efficiency, reducing system downtime, minimizing waste generation, and decreasing overall carbon emissions. The transition to Industry 5.0 amplifies the importance of IoT technologies in supporting sophisticated human-machine collaboration. Integrating IoT with advanced technologies such as artificial intelligence, edge computing, and cognitive systems creates intelligent environments where human expertise and machine capabilities complement each other. This evolution necessitates novel approaches to IoT education, particularly in developing practical skills that prepare professionals for the human-centric focus of Industry 5.0. This paper presents a comprehensive international collaboration initiative involving European universities and small and medium-sized enterprises (SMEs) in IoT education. Central to this initiative is the implementation of remotely controlled IoT laboratories, which embed IoT principles directly into the learning process. The establishment of innovative remote laboratories at the Silesian

University of Technology (Poland), Tallinn University of Technology (Estonia), and Riga Technical University (Latvia) represents a significant advancement in IoT education. These facilities are interconnected through the VREL universal access portal, facilitating resource sharing and expanding student access to IoT studies. The educational framework is supported by newly developed advanced IoT learning materials, encompassing crucial topics such as IoT design methodologies, architectures, data analysis, cybersecurity, blockchain, and green IoT. All educational resources are published under a Creative Commons (CC) license, ensuring widespread accessibility. Furthermore, these materials and practical laboratories are integrated into a massive open online course (MOOC), offered at no cost to participants. The initiative extends beyond traditional educational boundaries by introducing an international collaborative approach to master-level IoT education. The program is designed to attract diverse target groups, offering complete master's programs and individual courses for skill enhancement in IoT and cybersecurity. This paper details the development, implementation, and outcomes of this innovative educational platform, demonstrating how practical, hands-on experience with IoT technologies in an Industry 5.0 context can effectively prepare the next generation of industrial professionals while promoting sustainable and human-centric manufacturing practices.

2. State of the art

Remote and virtual laboratories in engineering education have evolved significantly since their inception in the early 1990s. Aburdene et al. (1991) proposed one of the first concepts of a remotely shared control systems laboratory, marking the beginning of remote laboratory development in engineering education. Throughout the 1990s, numerous remote laboratory solutions were developed based on the LabView software, as documented by Ertugrul (2000) in a comprehensive survey of teaching and learning tools. Early developments in this field include pioneering work at Tallinn University of Technology, where the first versions were proposed and implemented based on the LabView software and hardware components (Sell 2002; Sell and Otto 2009). Later, a whole stack of robotic remote laboratory concepts and practical solutions was developed and deployed across several universities and other schools (Seiler and Sell 2013; Sell et al. 2013). Partners of this research are also well known in remote and virtual lab developments, for example, virtual laboratory frameworks at Riga Technical University (Gravier et al. 2008; Nikitenko et al. 2014) and innovative remote automation laboratories at the Silesian University of Technology (Figwer and Czyż 2003). These developments, among many others globally, have contributed to the current state of remote and virtual laboratory education.

The terminology used in this domain often leads to confusion, particularly regarding the distinction between remote, distance, virtual, and online laboratories. Virtual laboratories, the most commonly implemented solution, operate in simulated environments hosted on servers without connection to physical hardware. These environments typically focus on programming virtual controllers and executing scripts within controlled, modeled conditions. Remote laboratories, on the other hand, represent a different approach by providing access to actual physical hardware through internet connectivity. In these settings, users can program and execute software on real controllers, interacting with physical devices remotely. A typical remote laboratory setup includes various peripheral devices connected to the microcontroller, such as LCDs, motors, lights, and sensors that provide real-time data. The validation of program execution is achieved through visual feedback, typically delivered via real-time camera feeds over the internet. This approach allows students to observe the actual behavior of their programs on physical hardware, providing a more authentic learning experience than purely simulated environments. Implementing remote laboratories varies significantly depending on the connected peripheral devices and the specific educational objectives. Online laboratories encompass both remote and virtual implementations, provided they are accessible through internet connectivity. Distance laboratories represent a broader category that includes any laboratory setup accessible from a distance, whether using physical or simulated equipment. This distinction is crucial as each type serves different educational purposes and offers unique advantages in engineering education. These systems have become increasingly sophisticated by integrating modern IoT technologies, enabling more complex interactions and data collection capabilities. The microcontroller-based remote laboratory setup remains a fundamental approach, offering flexibility in configuration while maintaining the essential connection to real-world hardware applications.

The current trend in IoT educational laboratories emphasizes the importance of standardization and interoperability. Recent implementations, such as those described by Ciolacu et al. (2023), have adopted standardized IoT protocols and interfaces, enabling easier integration with industrial systems and better preparation of students for real-world applications. These developments align with Industry 5.0 principles, particularly regarding human-centric design and sustainable technology implementation. Another significant trend in IoT educational laboratories is their expanding role in providing practical engineering education to a broader audience of remote students globally. This is particularly significant for developing regions, such as Sub-Saharan Africa, where access to sophisticated laboratory equipment is limited. As demonstrated by Kuaban et al. (2022), IoT-based remote laboratories can effectively support technological education in agriculture and food production sectors, providing practical skills development opportunities in regions with limited educational infrastructure. This development increasingly incorporates green IoT principles, addressing critical aspects of energy efficiency and sustainable operation of IoT devices (Kuaban et al. 2024), particularly relevant for regions with limited energy resources. Furthermore, these remote laboratories are particularly valuable for individuals facing various barriers to traditional education, including those with special needs or health conditions that might prevent physical presence in conventional laboratory settings.

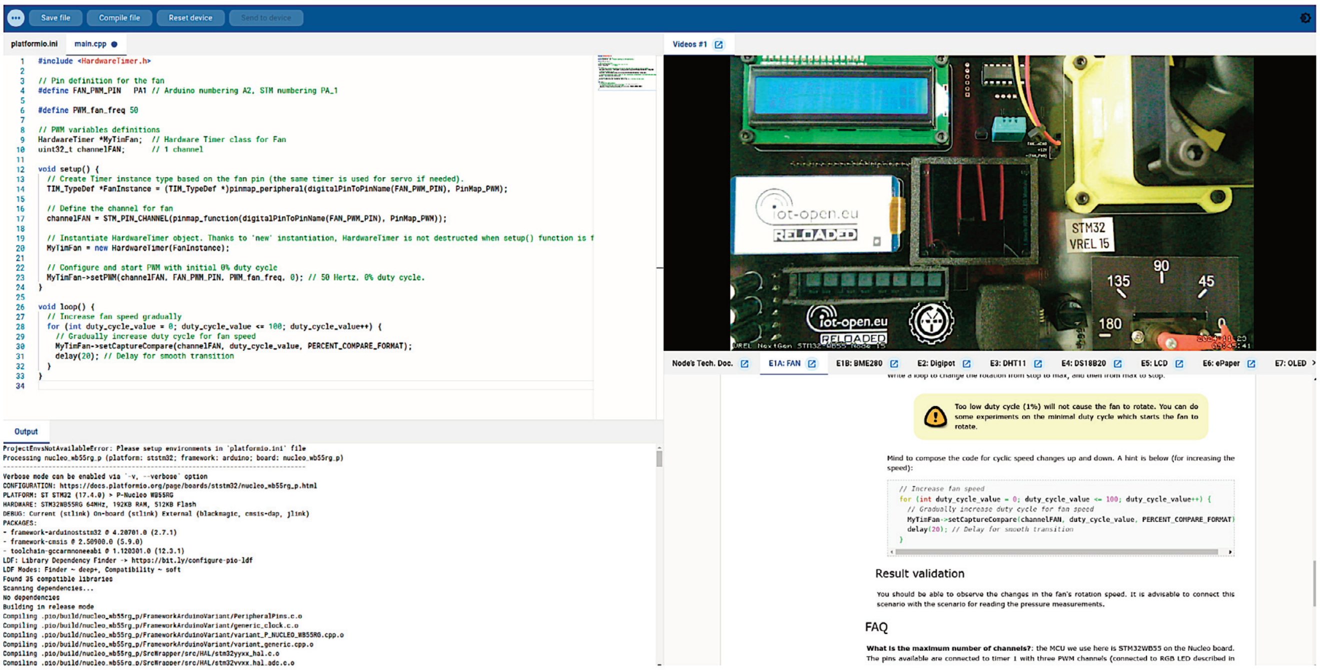

Fig. 1. Sample user interface of the VREL NextGen laboratory software section.

3. Remote IoT laboratory implementation: VREL NextGen platform

Modern engineering education faces multiple challenges in delivering practical IoT experience, particularly in non-traditional learning scenarios such as distance learning, MOOC course delivery, pandemic-related restrictions, and accommodation of diverse student needs. This aligns with the human-centric principles of Industry 5.0, as described by Nahavandi (2019), where technology adapts to human needs rather than humans adapting to technological constraints. The platform's ability to support students with different learning needs, including those with neurodivergent conditions such as Asperger syndrome, through self-paced study options exemplifies the inclusive, human-centered approach that characterizes Industry 5.0 educational frameworks. As noted by Xu et al. (2023), this adaptability in educational technology is crucial for developing future workforce capabilities while ensuring social inclusivity and sustainability.

The VREL NextGen laboratory platform addresses these challenges by providing comprehensive remote access to physical IoT hardware, avoiding the logistical and financial barriers of equipment purchase or rental. The platform supports multiple microcontroller units (MCUs), including STM, ESP, Atmel, and Raspberry Pi, with a flexible compilation infrastructure based on PlatformIO that extends to support various programming languages through customizable Linux commands. The system's primary design ensures that students require nothing beyond a web browser and network connectivity for regular use, making it particularly accessible for remote learning scenarios. The platform's technical implementation centers on a flexible device configuration system that enables programming in Python, MicroPython, and other languages through freely definable Linux commands. Laboratory nodes, particularly those utilizing MCU programming via serial connections, are managed through middleware platforms such as Raspberry Pi, which handles device programming, monitoring, and control. Students verify their work through three distinct channels: visual feedback via embedded web cameras, compiler output through standard I/O streams, and additional web-based services integration. Resource management features include exclusive device booking capabilities, user and group management, and virtual laboratory room organization. The platform implements several automation procedures for a zero-administration model, including user self-registration and default group access to selected devices. This automation particularly benefits public access scenarios such as open-source models or public demonstrations. The modern React-based frontend (Fig. 1) provides an intuitive interface for accessing these features, while the backend infrastructure ensures reliable device communication and resource allocation. VREL NextGen's implementation represents a significant advancement in remote IoT education, successfully addressing both technical and pedagogical requirements while maintaining accessibility and ease of use. This approach has proven valuable in ensuring continuous educational delivery during disruptions and supporting diverse learning needs across various educational contexts.

4. Implementation use cases of the VREL NextGen platform

The VREL NextGen platform has been implemented across three distinct educational institutions, each offering unique approaches to remote IoT laboratory education. These implementations demonstrate the platform's flexibility and adaptability to different educational needs and technical requirements.

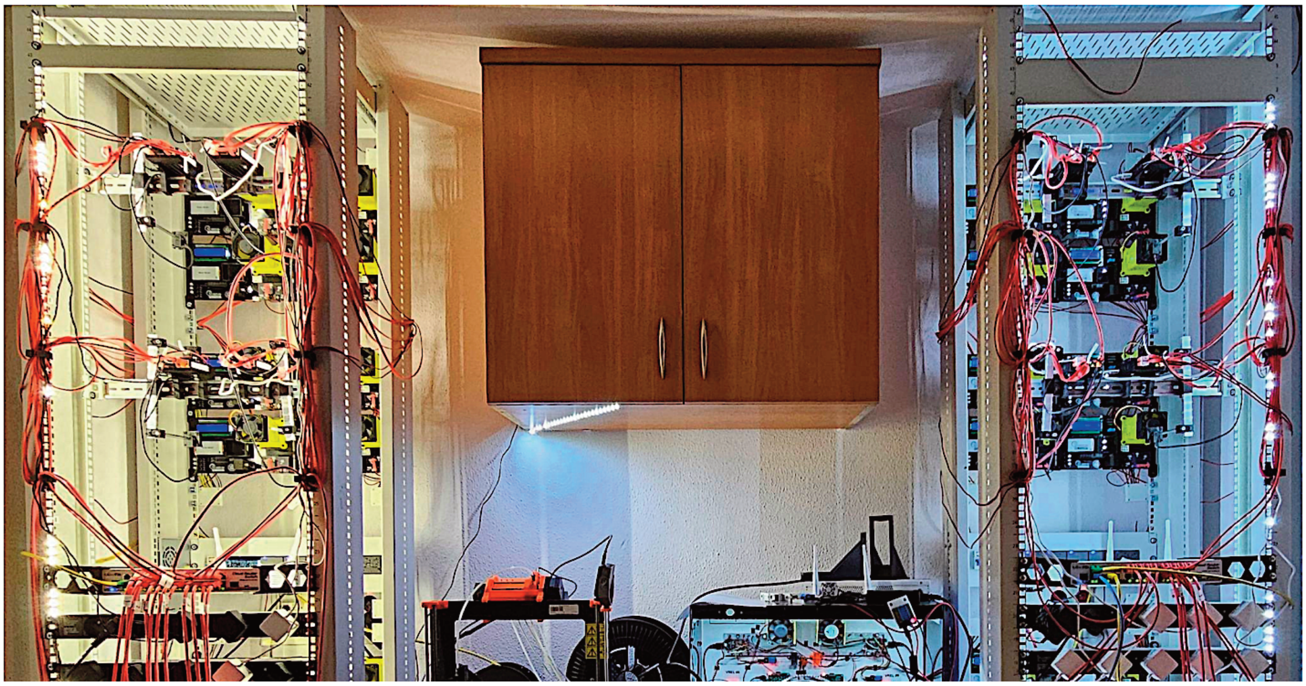

Fig. 2. VREL NextGen hardware laboratory nodes section at SUT. Photo taken by the authors.

4.1. Experimental online laboratories at the Silesian University of Technology

The Silesian University of Technology (SUT) has implemented an extensive IoT laboratory infrastructure consisting of 32 laboratory nodes, as presented in Fig. 2. Each node utilizes a universal motherboard design that accommodates various sensors and actuators with interchangeable MCUs. The implementation explicitly employs ESP32 and STM32 microcontrollers, chosen for their versatility and widespread industrial adoption. A key feature of the SUT implementation is its comprehensive networking infrastructure. The laboratory nodes are interconnected through MQTT bridges, enabling not only local device communication but also integration with external IoT devices and sensors globally. This connectivity creates a realistic IoT ecosystem where students can experience real-world networking scenarios and data exchange protocols. The hardware architecture employs a modular approach, with the universal motherboard serving as a standardized platform for various experimental configurations. This design philosophy allows for flexible reconfiguration of laboratory exercises while maintaining consistent interface standards and programming environments. Integrating ESP32 and STM32 platforms provides students with exposure to different microcontroller architectures and their respective programming paradigms.

4.2. Building management sensor network at Riga Technical University

Riga Technical University (RTU) has implemented an innovative dual-purpose approach, transforming its entire facility into a living IoT laboratory through a public-private partnership (PPP) with SAF Tehnika. The implementation features a comprehensive sensor network comprising 450 Aranet4 sensors distributed throughout the building, with each room equipped with at least one sensor for continuous environmental monitoring. The system focuses explicitly on tracking the thermodynamic behavior of the building while providing interactive capabilities through strategically placed pushbutton sensors. The system architecture leverages cloud-based infrastructure provided through the PPP, offering significant advantages in maintenance, cybersecurity, and scalability. The implementation provides both PUSH and PULL endpoints, enabling various educational scenarios, including malfunction detection, third-party data processing application development, and time-synchronous experimentation across different premises. This infrastructure supports RTU's multilayered educational approach, which combines distant labs for hardware experience, virtualization for scaled IoT system simulation, and the living lab environment for real-time data experimentation and predictive modeling. A distinctive feature of this implementation is its international reach, with the system being integrated with the Norwegian University of Science and Technology (NTNU). This cross-institutional collaboration enables a comparative analysis of building behavior across different geographical locations and environmental conditions. The cloud-based architecture, maintained by the industry partner, significantly reduces total ownership costs while ensuring robust cybersecurity through specialized API access for students and collaborators. The system has proven valuable not only for educational purposes but also as a data collection facility for research and innovation projects, demonstrating the versatility of the implementation. The simplified IoT system architecture and user interface are shown in Fig. 3.

4.3. IoT-robotics laboratory at Tallinn University of Technology

Tallinn University of Technology (TalTech) has taken an innovative approach to IoT-robotics education by repurposing existing medical equipment into a modern remote laboratory

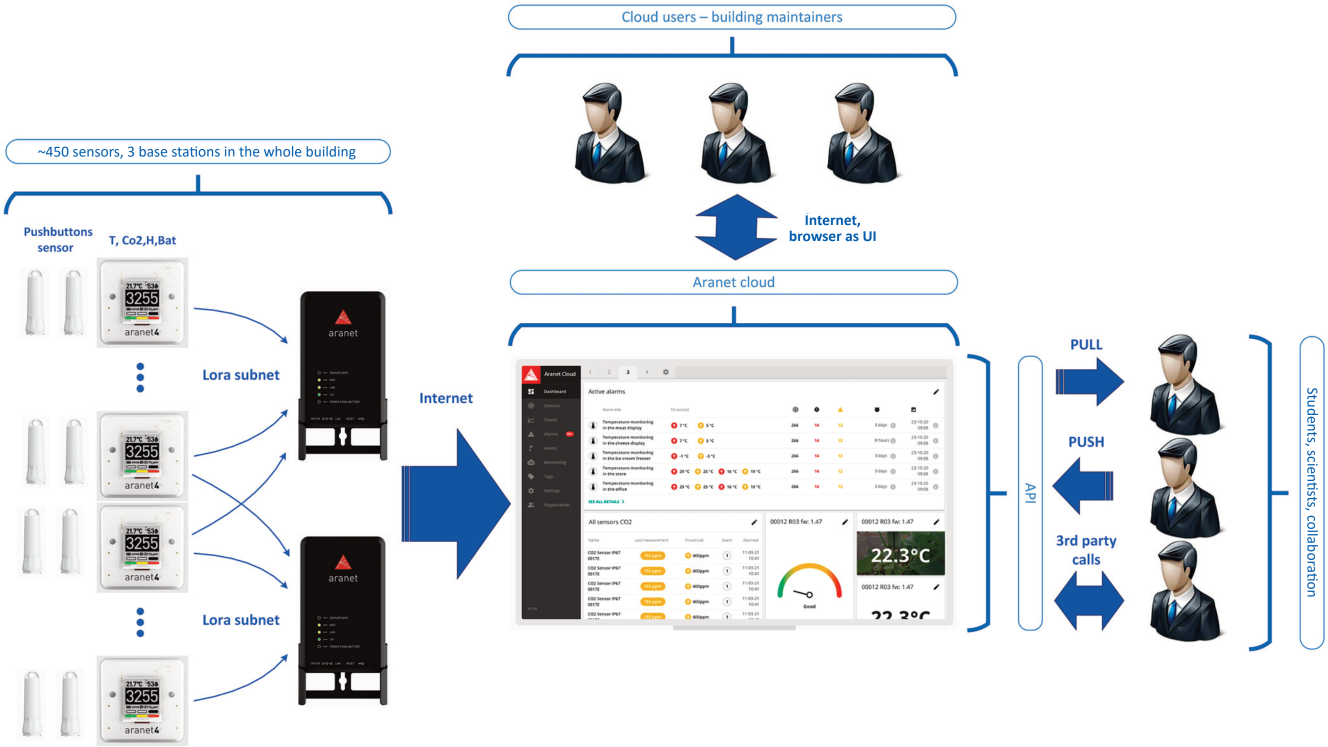

Fig. 3. Simplified system architecture and user interface of the RTU living lab.

platform. This implementation aligns with Industry 5.0 principles of human-robot cooperation and sustainability, where the converted Cartesian robot system serves as a practical example of human-centric automation. The laboratory setup demonstrates how traditional industrial robots can be adapted for collaborative scenarios, emphasizing the importance of human oversight and interaction in automated systems. The laboratory setup features a custom control system implemented using the widely accessible Arduino platform based on the AVR microcontroller architecture. The system utilizes stepper and DC motor drivers for precise motion control, making complex robotics concepts accessible through familiar hardware (Fig. 4). This implementation choice ensures that students can easily relate their laboratory experience to widely available components and transfer their knowledge to personal projects. The hardware architecture demonstrates practical applications of embedded systems in robotics control, from basic motor control to sophisticated human-robot interaction scenarios. This dual-purpose implementation serves both advanced IoT education and fundamental engineering principles. While master-level IoT students explore advanced concepts in human-robot collaboration and IoT integration, first-semester bachelor students use the same platform to study classical mechanical engineering concepts such as kinematics and dynamics. This multi-level educational approach exemplifies the Industry 5.0 principle of bridging traditional

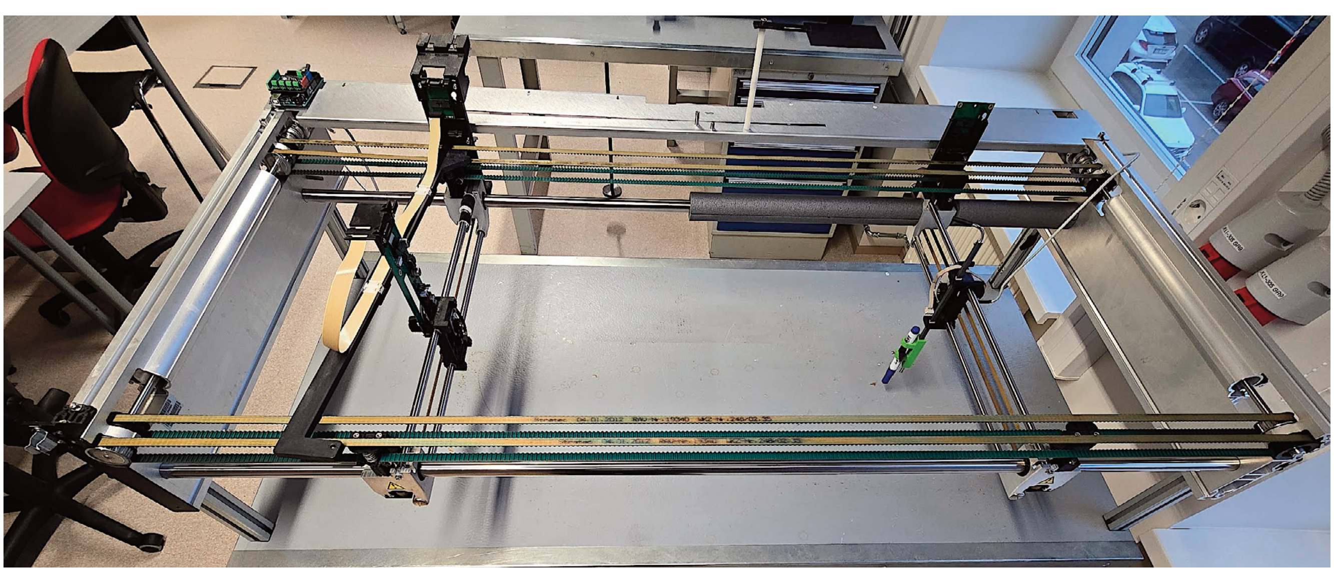

Fig. 4. Remote laboratory hardware of the TalTech IoT-robotic dual-purpose Cartesian robot system. Photo taken by the authors.

engineering disciplines with modern digital technologies. Repurposing medical equipment for educational purposes represents both sustainable laboratory development and an opportunity to study precision movement control in human-collaborative scenarios. The integration with the VREL platform enables remote programming and control of the robotic system, allowing students to experiment with both low-level microcontroller programming and high-level robotics concepts while considering human-machine interaction aspects. This approach helps students understand how automated systems can be designed to complement human capabilities rather than replace them, which is a key principle of Industry 5.0.

5. Conclusion

This paper has presented a comprehensive international approach to IoT education through the VREL NextGen platform, demonstrating how cross-institutional collaboration effectively addresses the challenges of modern engineering education. The successful implementation across three European universities showcases different yet complementary approaches to remote IoT education, establishing a robust model for resource sharing and standardized educational methodologies. Integrating diverse laboratory implementations – from microcontroller-based nodes to building-wide sensor networks and human-centric robotics platforms – provides students with broad exposure to IoT applications while aligning with Industry 5.0 principles. The platform's emphasis on human-centric design, sustainability, and resilience has proven crucial in preparing the next generation of engineering professionals, effectively bridging traditional engineering disciplines with emerging digital technologies. The success of this initiative demonstrates that international collaboration in engineering education can create rich learning environments that better prepare students for modern industrial settings. The platform's ability to support diverse educational scenarios while maintaining accessibility suggests a promising direction for engineering education in the Industry 5.0 era, establishing a foundation for future international collaborative efforts in technical education.

Data availability statement

All data are available in the article.

Acknowledgments

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Praktiline asjade interneti rahvusvaheline õppeplatvorm Tööstus 5.0 tarbeks

Raivo Sell, Piotr Czekalski, Krzysztof Tokarz, Godlove Suila Kuaban, Agris Nikitenko, Karlis Berkolds ja Łukasz Lipka

Artikkel tutvustab VREL NextGen platvormi kui terviklikku rahvusvahelist lahendust asjade interneti (IoT) õpetamiseks. Platvormi on edukalt rakendatud kolmes Euroopa ülikoolis, millest igaüks on välja töötanud erineva, kuid üksteist täiendava meetodi kaugõppe läbiviimiseks IoT valdkonnas. Õppekeskkond hõlmab mitmesuguseid laborirakendusi alates mikrokontrolleripõhistest seadmetest kuni hooneüleste sensorvõrkude ja inimkesksete robootikalahendusteni. See tagab tudengitele laiapõhjalise kogemuse IoT rakendustega, järgides samal ajal Tööstus 5.0 põhimõtteid. Erilist tähelepanu on pööratud inimkesksele lähenemisele, jätkusuutlikkusele ja vastupidavusele, mis on olulised tulevaste inseneride ettevalmistamisel ning traditsiooniliste ja uute digitehnoloogiate lõimimisel. Projekti edu näitab, et rahvusvaheline koostöö tehnikahariduses võib luua mitmekesise ja sisuka õpikeskkonna, mis valmistab tudengeid paremini ette tänapäevaseks tööstuskeskkonnaks. Platvormi võimekus toetada erinevaid õppestsenaariume, säilitades samal ajal hea ligipääsetavuse, loob tugeva aluse tulevastele rahvusvahelistele koostööprojektidele tehnilise hariduse vallas Tööstus 5.0 ajastul.