Integration of laboratory equipment in remote learning environments

Liudmyla V. Vasylieva[1], Denys Yu. Mikhieienko[1] and Iryna A. Getman[1]

[1]*Donbas State Engineering Academy, 72 Akademichna Str., Kramatorsk, 84313, Ukraine*

Abstract

This research examines the integration and implementation strategies for laboratory work within remote learning environments, alongside an analysis of virtual laboratories as an alternative to traditional practical training. We investigate the distinct challenges faced by higher education institutions in laboratory instruction during the COVID-19 pandemic, drawing upon international commission data. The study critically evaluates the advantages and limitations of remote laboratory execution, particularly focusing on the complexities of transitioning from physical to virtual experimentation. Through a detailed case study of a bioelectronics and biomechanics laboratory, we demonstrate the feasibility of remote laboratory access via Internet-based solutions. The research concludes by proposing strategic directions for the advancement of virtual practical work within the computer information technologies department, contributing to the broader discourse on the future of practical education in digital environments.

Keywords

technology-enhanced learning, remote laboratory instruction, virtual experimentation, computer-numerical control systems, additive manufacturing

1. Introduction

The digitalisation of higher education has been progressively advancing [1, 2], with institutions increasingly migrating educational materials and activities onto virtual learning platforms such as Moodle and Blackboard [3]. However, the unprecedented circumstances precipitated by the COVID-19 pandemic and ongoing Russian invasion of Ukraine have catalysed an extraordinary transformation in pedagogical approaches [4, 5], particularly in laboratory-based instruction. This paradigm shift has necessitated the rapid transition of traditional classroom environments to virtual spaces, facilitated by video conferencing platforms such as Zoom, Webex, and Microsoft Teams.

The Department of Computer Information Technologies at Donbas State Engineering Academy, like numerous institutions globally, faced the imperative to transition to remote learning modalities. However, a significant challenge emerged regarding the practical component of technical education – specifically, laboratory work requiring specialised equipment. This challenge is particularly acute in technical disciplines, where the development of professional competencies is inextricably linked to hands-on laboratory experience.

The integration of laboratory work within remote learning environments thus presents a critical pedagogical challenge that demands innovative solutions. The *aim* of this research is to investigate the feasibility and methodological approaches for conducting laboratory work in remote learning contexts, with particular emphasis on maintaining educational quality and practical skill development.

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vasileva.dgma@gmail.com (L. V. Vasylieva); mixey80@gmail.com (D. Yu. Mikhieienko); getman_irina@ukr.net (I. A. Getman)
http://www.dgma.donetsk.ua/vasileva-lyudmila-volodimirivna.html (L. V. Vasylieva);
http://www.dgma.donetsk.ua/miheenko-denis-yuriyovich.html (D. Yu. Mikhieienko);
http://www.dgma.donetsk.ua/getman_irina-anatoliyivna.html (I. A. Getman)
0000-0002-9277-1560 (L. V. Vasylieva); 0000-0003-1966-0618 (D. Yu. Mikhieienko); 0000-0003-1835-4256 (I. A. Getman)

2. Related work

Consideration of the specifics of conducting a laboratory workshop in a distance learning environment should begin with a consideration of the specifics of education in the context of the coronavirus pandemic in general. The pandemic, on a global scale, has affected not only all spheres of public life [6], but also each person individually, and not only on the physical but also on the psycho-emotional levels [7, 8]. This was especially acutely felt by the education sector since it required a total transfer of all educational activities to a distance mode. According to Executive Director of Chandigarh University (India) S. K. Tripath, "The new coronavirus has affected employment, education, energy, agriculture and other areas of the global economy, including the emotional state of citizens. Higher education institutions (HEIs), including universities, colleges and other institutions of higher education, are no exception" [9]. According to UNESCO, the COVID-19 pandemic has led to the largest disruption in education systems in history, affecting nearly 1.6 billion students in more than 190 countries and on all continents. School and other educational closures have affected 94% of the global student population, with 99% in low- and lower-middle-income countries [10]. According to the same UNESCO, 826 million students in the world do not have personal computers, 706 million (43%) do not have access to the Internet [11].

In high school, the use of web-based distance education is expanding rapidly [12]. This requires constant improvement of the technological and methodological support of the educational process. Failure in education is a serious threat to the entire society. Therefore, educational institutions must respond quickly and ensure the continuity of educational processes. Research is underway to develop technical, organizational, and pedagogical changes that educational institutions must implement to use different methods of interaction, ensure continuity and provide high-quality education [13].

Research on the advantages and disadvantages of distance education is important [14]. Many universities are researching to examine the effectiveness of distance learning at universities in light of the coronavirus pandemic and to identify the barriers that university students face [15]. Bataineh et al. [16] is pointed out that distance learning requires an exceptional environment, ability, and IT skills in addition to smart devices and applications that enable video conferencing. Another important area is the study of methods and means for involving students in the online learning process [17]. An important step in the transition to online of many laboratories that are used in higher education, especially in STEM fields [18, 19, 20, 21]. This is important for students of those specialties that require access to physical objects: devices, sensors, control devices. One of the ways to solve this problem is to use remote lab and virtual lab technologies when programming an embedded system and applying them to managing technical objects [22, 23, 24]. A virtual laboratory is a software and hardware complex that allows research without direct contact with real production or educational equipment, or in the absence of it [23, 25, 26]. The remote lab includes real technological equipment, software, and hardware for controlling the technological complex and analog-digital conversion of measuring signals from sensors installed on the equipment. At the same time, it should be ensured: the operation of the equipment, a reliable access channel via the Internet, access dispatching and accounting of work performed, video stream transmission using appropriate equipment, etc. These tasks are solved, for example, in the GOLDi system [27]. Within the GOLDi remote lab, interactive content objects can be offered to students to digitally support learning processes. These are digital, immersive tools that allow you to explore learned content with predefined or self-created examples. Virtual lab emulates laboratory equipment through the use of mathematical models [28, 29]. It is also necessary to improve the technologies of the educational process based on the use of IT.

To ensure a proper response to emerging problems, universities need to focus on changing not only teaching methods but also the very approaches to teaching, organizing the educational process, and to do this quality and quickly. On the other hand, it became necessary to abandon the traditional method of planning and implementing educational programs. A regulatory component of the educational process during a pandemic in the Donbas State Engineering Academy was the "Regulations on distance learning for applicants for higher education at the Donbas State Engineering Academy in special conditions" [30]. The implementation of this provision is based on the expansion of distance learning opportunities through the digitalization of education, which, on the one hand, requires an analysis of the digital infrastructure of the academy, and on the other, its management. This analysis led to the solution of a global problem for technical universities – how to implement a laboratory practice on special equipment in this mode.

All laboratory work can be classified according to the type of disciplines where they are used. This applies more to special disciplines, where the student is often given the task of measuring the characteristics of any process using real devices or maintaining the process occurring in a given state. It is also possible to set some target state, which should be achieved in the process of laboratory experiment by appropriate actions of the student [31].

3. Case study

Consider the possibilities and ways of remote use of laboratory equipment of laboratories of bioelectronics and biomechanics of the Department of Computer Information Technologies of Donbas State Engineering Academy. They are equipped with modern research and production equipment that was purchased as part of the work in the international project BioArt Erasmus+ and allows research on the use of modern computer information technology in electronics, mechanics, biomechanics, and mechatronics. The production equipment of the laboratories includes machines with computer numerical control (CNC) and a 3D printer. This equipment allows to significantly expand the experience of students in the field of computer modeling and automated design in such CAD-systems as AutoCAD (2D modeling) SolidWorks and PTC Creo (3D modeling) by moving from computer models of objects to their material embodiment.

Computer numerical control means a computerized control system that reads the instructions of a specialized programming language and controls the drives of metal, wood, and plastic machining machines and machine tools. The CNC system interpreter translates the program from the input language to the control commands of the main drive, feed drives, controllers of the machine units (enable / disable cooling, for example). To determine the required trajectory of the working body as a whole (tool/work piece) by the control program (CP) uses an interpolator that calculates the position of the intermediate points of the trajectory specified in the program end. CNC machining increases productivity and accuracy of operations, guarantees a constant level of quality, which in most cases far exceeds the quality of traditional manual machining. Many orders that previously had to be abandoned can now be fulfilled easily and effortlessly, which in the meantime is considered exclusive and is the category of the largest profit [32].

CNC machines are represented by the following models. CNC machine Krechet-4060 manufactured by the Ukrainian company "CNC machines" (figure 1). This machine can be used for 2D and 3D milling of all types of plastics, wood, plywood, MDF, foam, composite, and light metals. The working field of the machine 400 x 600 mm, stroke on the Z-axis 100 mm, processing error 0.08 mm.

Figure 1: CNC machine Krechet-4060.

These are the Sherline 5410 CNC drilling and milling machine and the Sherline 4410 CNC lathe (figure 2). Sherline is located in the United States and is widely known in the world for quality small machines. These machines allow you to perform machining of parts in both software and manual control mode. The free version of Mach 3 is used as software for controlling motor controllers. It is enough to control the processing of medium-sized parts.

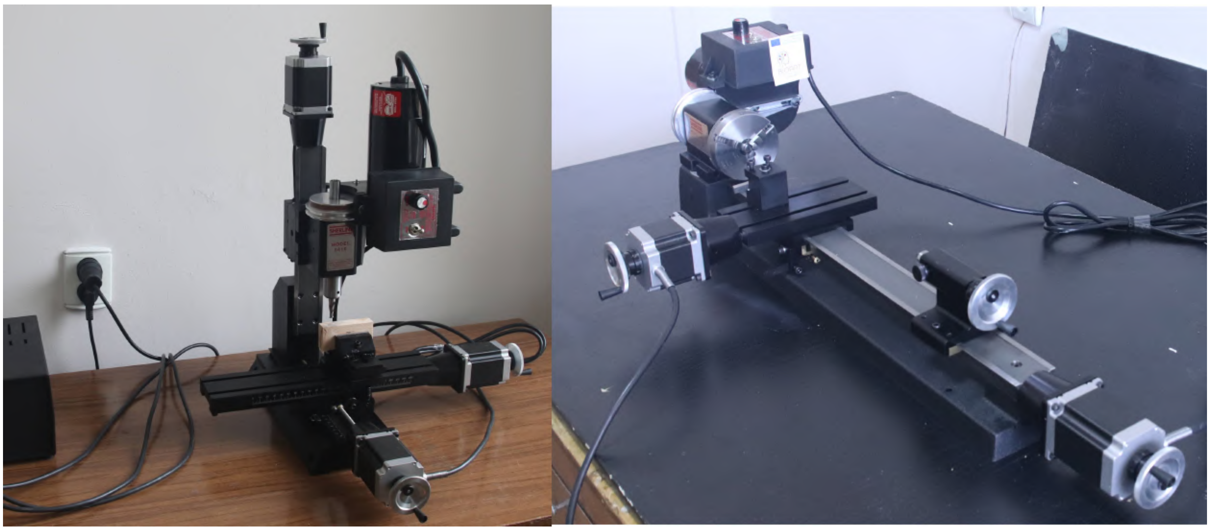

Figure 2: CNC machines: Sherline 5410 CNC and Sherline 4410 CNC.

The Sherline 5410 CNC drilling and milling machine have a motor power of 0.6 kW, a spindle speed range of 70–2800 rpm, axial movement: X/Y/Z – 220/127/159 mm, respectively. Stepper motors to control the movement of the axes with a capacity of 0.2 kW.

The Sherline 4410 CNC lathe has a motor power of 0.6 kW, spindle speed range 70–2800 rpm, spindle bore diameter 10 mm, rear headstock quill stroke 45 mm, rear headstock quill cone – MK1, turning diameter over frame 180 mm, turning diameter above the transverse caliper 90 mm, the distance between the centers 430 mm, the course of the transverse caliper 110 mm. Stepper motors to control the movement of the axes with a capacity of 0.2 kW. There is a complete set of equipment that allows you to process not completely cylindrical parts and cut threads. The machine allows to carry out processing with simultaneous movement of the tool on two coordinates.

Additive technologies have made a big qualitative leap in recent years, moving from the category of industrial equipment to personal devices. Due to this, there is an opportunity for the widespread introduction of this technology in the educational process. This allows not only to refine and expand the classic laboratory workshop but also to increase students' motivation and develop their competencies in the field of new technologies and their practical application.

In the conditions of active modernization of education, equipping universities with modern computer technology and transition to various forms of e-learning, there is an active introduction into the educational process of various virtual simulators and complexes designed to replace real physical experiment, the base of which is often not updated and obsolete over time. But a real physical experiment plays a very important role in the learning process. It allows not only to instill skills in working with equipment, but also to develop research and cognitive interest in students [33].

The presence of a large number of 3D printing technologies on the one hand gives a wide field for choice, on the other hand, imposes certain restrictions on their implementation. One of the most common 3D printing technologies is FDM (fused deposition modeling).

Among the main advantages of this type of printing are the following:

- the use of fairly compact printing devices that do not require special knowledge and skills in installation and operation;

- relatively low (compared to devices that use other technological processes) cost, both the devices themselves and consumables;
- the principle of the press is simple and technological that does not demand special places of installation;
- openness of technology, i.e. the possibility of its improvement and modification (the possibility of assembling a printing device from a ready-made designer or set of components).

Equipment for additive production in laboratories is represented by a 3D printer FARM2 (figure 3). This 3D printer has a printing area of 200x200x200 mm, implements ULTIMAKER kinematics, and has the ability to print the following types of plastic: PLA, ABS, PVA, Nylon, HDPE, PCL, PET-G.

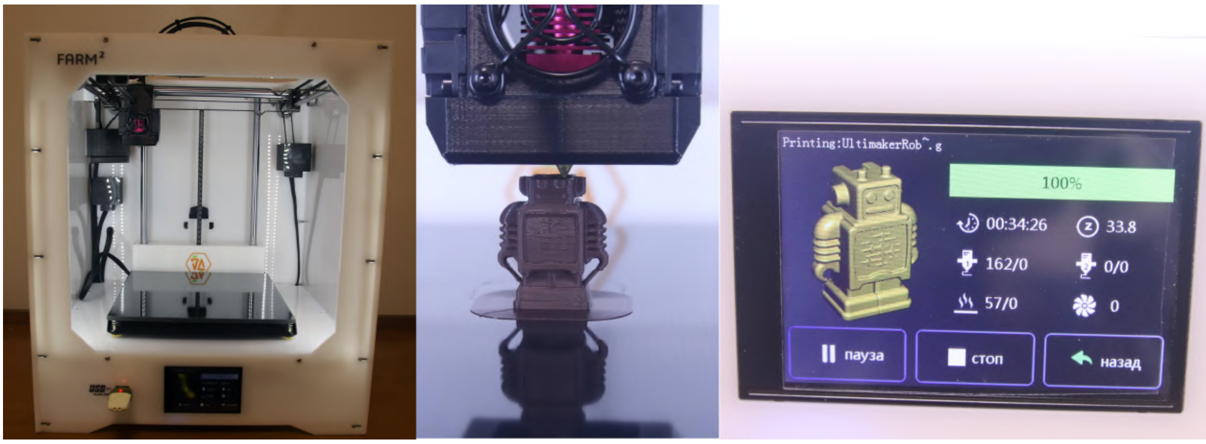

Figure 3: 3D printer FARM2.

Let's move directly to consider the possibility of remote laboratory work on CNC machines and 3D printers. Unfortunately, at the moment, for the full operation of machines and printers, some operations can only be performed by humans. For CNC machines it is the installation and replacement of working tools, blanks and finished products, chip cleaning. For 3D printers, this is a replacement for plastic and printed models. Although for some of these operations there is already a solution for full or partial automation (tool replacement and chip removal), laboratory work on CNC machines and 3D printers without the intervention of a teacher or laboratory assistant is currently impossible. But, despite this, it is already possible to remotely monitor the operation of CNC machines and 3D printers, get the parameters of their work and quickly adjust them. Consider ready-made solutions in this area.

In [34] the possibility of quality control and remote control of the device using a server is considered. The development of a server for CNC machine tool management is considered in order to improve the user experience and expand the capabilities of the device, including remote monitoring of the device. The work is based on the implementation of synchronous engine control using such parameters as: Constant snap period, Constant jerk period, Constant acceleration period, Constant velocity period, and imposed snap bound. This set of parameters is a classic for CNC machines. To control the device, it uses a simple built-in system (single-board computer) Beaglebone Black with control through the OS Linux kernel, acting as an operating system. Due to the choice of OS Linux as the operating system, the firmware software is open source.

To implement the firmware used a patch RTLinux [35], designed to work with components in real-time. The exchange of information between blocks in real-time is through shared memory. A program in C++ using a server on Linux was developed for remote device management. The program works as a server processing client requests. To implement the client part in the course of work were considered 3 options: a console application on Linux, a console application on Windows, and an application with a graphical interface. PRUSS firmware was developed to perform real-time calculations. The server application used writes data to the shared memory, which uses the PRUSS firmware to generate control signals and exchange their states via GPIO. The board and computer interact via a TCP connection via an Ethernet port.

One of the most common open-source firmware for remote control of 3D printers is the RepRap system. In [36] its application is considered. The web server is developed in Python in conjunction with the Tornado framework. The authors highlight some advantages of using the above framework to implement the server. The main advantage is the lightness of the system and the ability to scale to service up to tens of thousands of open connections, which is well suited for the operation of the printer management system during long-term use of the connection. The paper describes in detail the principle of client-server communication based on the HTTP protocol, which allows studying in detail the process of information transfer. The client part is a web page. As a result of firmware research, promising directions of technology development are proposed, including improving the functionality of the remote Rep-Rap server.

To improve the user experience when working with printing devices, the capabilities of 3D printers need to ensure their extensibility. One of these modifications is to provide full or partial tracking of the behavior of device modules. Monitoring the printing process requires access to readings from various types of sensors and printer components. Monitoring the printing process requires access to readings from various types of sensors and printer components. This system allows you to automate the collection of information about the device for subsequent display of data to the user to analyze the operation of the printer. There are also more advanced technologies for tracking the printing process, in which the status of the printer is monitored by analyzing readings from sensors and the position of the head using a neural network [37]. The article analyzes the operation of the position sensor, which is used to collect data on the status of the printer. It uses the prediction root mean square error as an indicator to describe the operating state of the printer. As a prospect for the development of technology, the introduction of such analysis into the remote control system of a 3D printer should be considered, it will allow monitoring the quality of the printing process and remotely monitoring the health of the device.

Also, many amateur projects for remote control of 3D printers on the use of open-source software (more often OctoPrint) and single-board computers Raspberry Pi and Orange Pi are posted in the public domain.

Consider the ways of remote use of equipment for research and development. The study of the mechanical properties of medical purposes, for example, metals, composites, threads, are investigated on a universal testing machine UIT STM 001, which can be completed with a variety of equipment and devices, and the software allows testing according to various standards (GOST, GB, ASTM, DIN, ISO, etc.) and techniques (figure 4). Using an application programming interface (API) allows you to develop software products to extend the capabilities of the testing machine.

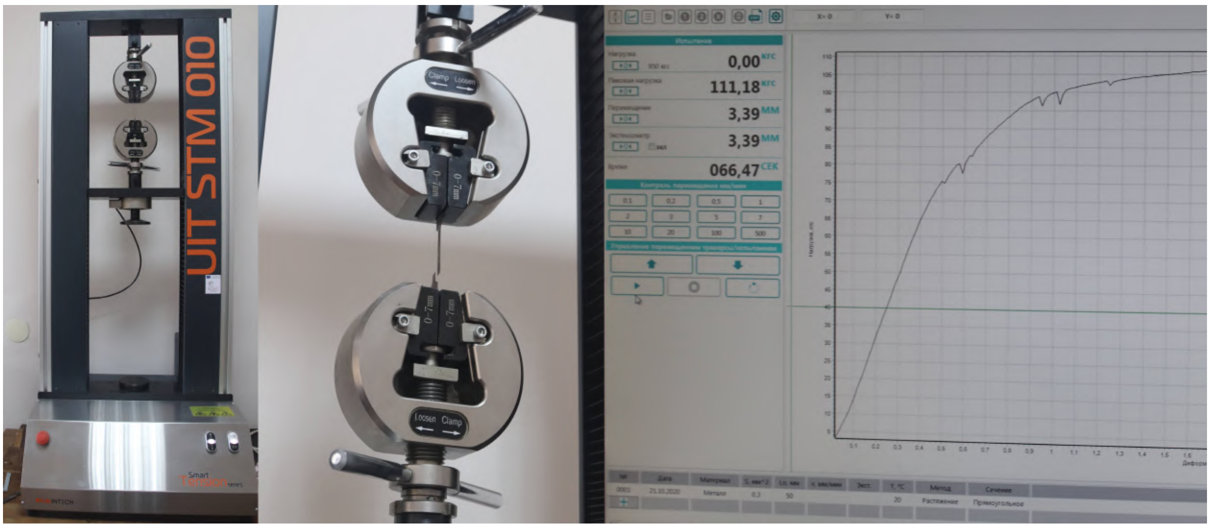

Figure 4: Universal testing machine UIT STM 001.

Full automation of the testing machine has the same obstacles as the automation of machine tools and 3D printers - human intervention is required, in the case of a testing machine, to replace prototypes. The ways of partial remote translation of laboratory work on a testing machine are also similar – remote monitoring and control.

But in the case of a testing machine, an alternative way is possible – replacing real laboratory works with virtual ones [38, 39, 40]. In [28], a prototype of virtual laboratory work was developed for use in the educational process in the course “Resistance of materials”. The software package in real-time provides a full cycle of laboratory work: preparatory stage (training), installation and removal of the sample, performing measurements of the sample before and after testing, test, plotting a tensile diagram to determine the main mechanical strength characteristics (figure 5). The tests have shown that the use of modern technologies for performing virtual laboratory work in the educational process significantly increases the quality and efficiency of the learning process and can be used in conjunction with work on real equipment.

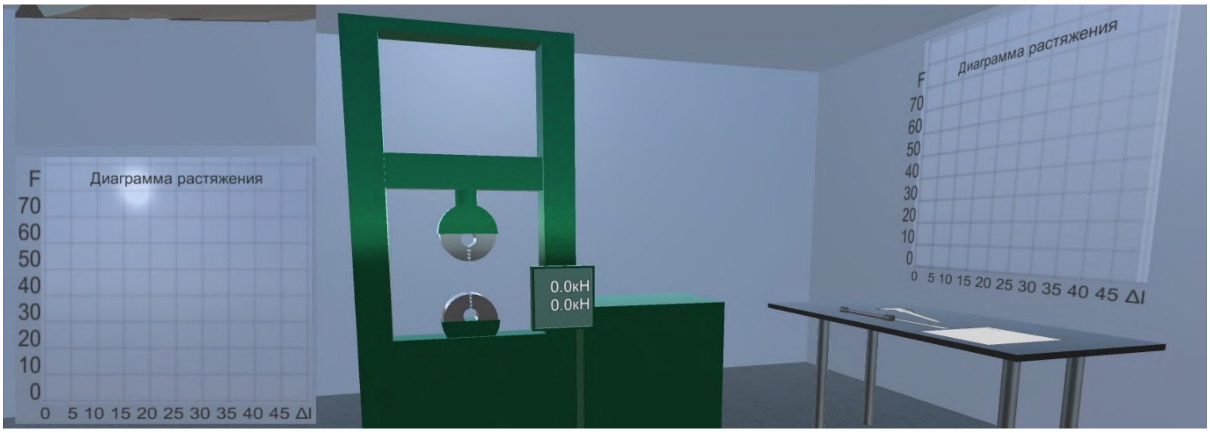

Figure 5: Program interface with three-dimensional models, interface, and mini cameras for simultaneous control of all processes [28].

Experience has shown that most students had no problems with running the labs and completing them. We believe that the best result is achieved when they are conducted in real-time, with the teacher’s explanations via video link and dialogue with the students.

4. Conclusion

Developed courses are at the stage of implementation in the educational process. The study of the features of laboratory work in the conditions of distance learning showed:

- at this point, it is impossible to make complete automation of equipment for remote laboratory work. Human intervention is required for some operations. This makes it relevant to develop communications between students, teachers, and laboratory assistants using modern electronic means of communication, planning, and optimization of the working time of laboratory equipment;
- there are many ready-made solutions for remote monitoring and control of laboratory equipment using open source software, single-board computers, cloud services, server, and client applications;
- in some cases, an alternative to laboratory work on real equipment is to replace them with virtual laboratory works.

The authors do not view the virtual labs as a complete substitute for the real ones. However, we think that they will organically complement classroom work after the pandemic and war are over.

References

[1] A. V. Morozov, T. A. Vakaliuk, I. A. Tolstoy, Y. O. Kubrak, M. G. Medvediev, Digitalization of thesis preparation life cycle: a case of Zhytomyr Polytechnic State University, in: T. A. Vakaliuk, V. V. Osadchyi, O. P. Pinchuk (Eds.), Proceedings of the 2nd Workshop on Digital Transformation of Education (DigiTransfEd 2023) co-located with 18th International Conference on ICT in Education, Research and Industrial Applications (ICTERI 2023), Ivano-Frankivsk, Ukraine, September 18-22, 2023, volume 3553 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2023, pp. 142–154. URL: https://ceur-ws.org/Vol-3553/paper14.pdf.

[2] O. V. Bondarenko, O. V. Hanchuk, O. V. Pakhomova, I. M. Varfolomyeyeva, Digitalization of geographic higher education: Problems and prospects, Journal of Physics: Conference Series 2611 (2023) 012015. doi:10.1088/1742-6596/2611/1/012015.

[3] L. Fadieieva, S. Semerikov, Exploring the Interplay of Moodle Tools and Student Learning Outcomes: A Composite-Based Structural Equation Modelling Approach, in: E. Faure, Y. Tryus, T. Vartiainen, O. Danchenko, M. Bondarenko, C. Bazilo, G. Zaspa (Eds.), Information Technology for Education, Science, and Technics, volume 222 of *Lecture Notes on Data Engineering and Communications Technologies*, Springer Nature Switzerland, Cham, 2024, pp. 418–435. doi:10.1007/978-3-031-71804-5_28.

[4] S. O. Semerikov, T. A. Vakaliuk, I. S. Mintii, V. A. Hamaniuk, V. N. Soloviev, O. V. Bondarenko, P. P. Nechypurenko, S. V. Shokaliuk, N. V. Moiseienko, V. R. Ruban, Mask and Emotion: Computer Vision in the Age of COVID-19, in: Digital Humanities Workshop, DHW 2021, Association for Computing Machinery, New York, NY, USA, 2022, p. 103–124. doi:10.1145/3526242.3526263.

[5] S. O. Semerikov, T. A. Vakaliuk, I. S. Mintii, S. O. Didkivska, Challenges facing distance learning during martial law: results of a survey of Ukrainian students, Educational Technology Quarterly 2023 (2023) 401–421. doi:10.55056/etq.637.

[6] S. Semerikov, S. Chukharev, S. Sakhno, A. Striuk, V. Osadchyi, V. Solovieva, T. Vakaliuk, P. Nechypurenko, O. Bondarenko, H. Danylchuk, Our sustainable coronavirus future, E3S Web of Conferences 166 (2020) 00001. doi:10.1051/e3sconf/202016600001.

[7] M. Velykodna, Psychoanalysis during the COVID-19 pandemic: Several reflections on countertransference, Psychodynamic Practice 27 (2021) 10–28. doi:10.1080/14753634.2020.1863251.

[8] M. Velykodna, I. Frankova, Psychological support and psychotherapy during the COVID-19 outbreak: First response of practitioners, Journal of Intellectual Disability - Diagnosis and Treatment 9 (2021) 148–161. doi:10.6000/2292-2598.2021.09.02.1.

[9] COVID-19 i Vysshee obrazovanie: Otuchitsia ot prezhnikh navykov radi sozdaniia sistemy obrazovaniia na budushchee (COVID-19 and Higher Education: Unlearn Previous Skills to Build Education for the Future), 2020. URL: https://www.un.org/ru/85374.

[10] International Commission on the Futures of Education, Education in a post-COVID world: Nine ideas for public action, United Nations Educational, Scientific and Cultural Organization, Paris, 2020. URL: https://unesdoc.unesco.org/ark:/48223/pf0000373717/PDF/373717eng.pdf.multi.

[11] R. Faek, T. A. El-Galil, The shift to online education in the arab world is intensifying inequality, 2020. URL: https://www.al-fanarmedia.org/2020/04/the-shift-to-online-education-in-the-arab-world-is-intensifying-inequality/.

[12] I. S. Mintii, T. A. Vakaliuk, S. M. Ivanova, O. A. Chernysh, S. M. Hryshchenko, S. O. Semerikov, Current state and prospects of distance learning development in Ukraine, CEUR Workshop Proceedings 2898 (2021) 41–55. URL: http://ceur-ws.org/Vol-2898/paper01.pdf.

[13] Ž. Bojović, P. D. Bojović, D. Vujošević, J. Šuh, Education in times of crisis: Rapid transition to distance learning, Computer Applications in Engineering Education 28 (2020) 1467–1489. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/cae.22318. doi:10.1002/cae.22318.

[14] Advantages and disadvantages of distance learning, 2017. URL: https://www.eztalks.com/elearning/advantages-and-disadvantages-of-distance-learning.html.

[15] D. Y. Bobyliev, E. V. Vihrova, Problems and prospects of distance learning in teaching fundamental subjects to future mathematics teachers, Journal of Physics: Conference Series 1840 (2021) 012002.

doi:10.1088/1742-6596/1840/1/012002.

[16] K. B. Bataineh, M. S. Atoum, L. A. Alsmadi, M. Shikhali, A silver lining of coronavirus: Jordanian universities turn to distance education, International Journal of Information and Communication Technology Education 17 (2021) 138–148. URL: https://www.igi-global.com/gateway/article/260754. doi:10.4018/IJICTE.20210401.oa1.

[17] Z. Chen, J. Jiao, K. Hu, Formative assessment as an online instruction intervention: Student engagement, outcomes, and perceptions, International Journal of Distance Education Technologies 19 (2021) 50–65. URL: https://www.igi-global.com/gateway/article/264397. doi:10.4018/IJDET.20210101.oa1.

[18] S. O. Semerikov, M. M. Mintii, I. S. Mintii, Review of the course "Development of Virtual and Augmented Reality Software" for STEM teachers: implementation results and improvement potentials, in: S. H. Lytvynova, S. O. Semerikov (Eds.), Proceedings of the 4th International Workshop on Augmented Reality in Education (AREdu 2021), Kryvyi Rih, Ukraine, May 11, 2021, volume 2898 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2021, pp. 159–177. URL: https://ceur-ws.org/Vol-2898/paper09.pdf.

[19] R. P. Kukharchuk, T. A. Vakaliuk, O. V. Zaika, A. V. Riabko, M. G. Medvediev, Implementation of STEM learning technology in the process of calibrating an NTC thermistor and developing an electronic thermometer based on it, in: S. Papadakis (Ed.), Joint Proceedings of the 10th Illia O. Teplytskyi Workshop on Computer Simulation in Education, and Workshop on Cloud-based Smart Technologies for Open Education (CoSinEi and CSTOE 2022) co-located with ACNS Conference on Cloud and Immersive Technologies in Education (CITEd 2022), Kyiv, Ukraine, December 22, 2022, volume 3358 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2022, pp. 39–52. URL: https://ceur-ws.org/Vol-3358/paper25.pdf.

[20] M. M. Mintii, N. M. Sharmanova, A. O. Mankuta, O. S. Palchevska, S. O. Semerikov, Selection of pedagogical conditions for training STEM teachers to use augmented reality technologies in their work, Journal of Physics: Conference Series 2611 (2023) 012022. doi:10.1088/1742-6596/2611/1/012022.

[21] M. M. Mintii, STEM education and personnel training: Systematic review, Journal of Physics: Conference Series 2611 (2023) 012025. doi:10.1088/1742-6596/2611/1/012025.

[22] J. G. Zubía, G. R. Alves (Eds.), Using Remote Labs in Education: Two Little Ducks in Remote Experimentation, University of Deusto, Bilbao, 2011. URL: http://www.deusto-publicaciones.es/deusto/pdfs/otraspub/otraspub01.pdf.

[23] E. Sancristobal, S. Martín, R. Gil, P. Orduña, M. Tawfik, A. Pesquera, G. Diaz, A. Colmenar, J. García-Zubia, M. Castro, State of art, initiatives and new challenges for virtual and remote labs, in: 2012 IEEE 12th International Conference on Advanced Learning Technologies, 2012, pp. 714–715. doi:10.1109/ICALT.2012.232.

[24] O. Tsvetkova, O. Piatykop, A. Dzherenova, O. Pronina, T. A. Vakaliuk, I. Fedosova, Development and implementation of virtual physics laboratory simulations for enhanced learning experience in higher education, in: S. Papadakis (Ed.), Proceedings of the 11th Workshop on Cloud Technologies in Education (CTE 2023), Kryvyi Rih, Ukraine, December 22, 2023, volume 3679 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2023, pp. 98–110. URL: https://ceur-ws.org/Vol-3679/paper10.pdf.

[25] S. Malchenko, From smartphones to stargazing: the impact of mobile-enhanced learning on astronomy education, Science Education Quarterly 1 (2024) 1–7. doi:10.55056/seq.816.

[26] D. A. Karnishyna, T. V. Selivanova, P. P. Nechypurenko, T. V. Starova, S. O. Semerikov, Enhancing high school students' understanding of molecular geometry with augmented reality, Science Education Quarterly 1 (2024) 25–40. doi:10.55056/seq.818.

[27] GOLDi : The Grid of Online Laboratory Devices Ilmenau, 2021. URL: http://goldi-labs.net/.

[28] L. V. Vasilyeva, A. S. Portnyagin, Implementation of a simulator of a specialized explosive machine for conducting virtual laboratory work, Scientific papers of Donetsk National Technical University: Informatics, Cybernetics and Computer Science 24 (2017) 30–35. URL: http://nbuv.gov.ua/UJRN/Npdntu_inf_2017_1_6.

[29] O. Tarasov, L. Vasylieva, O. Altukhov, V. Anosov, Automation of the synthesis of new design

solutions based on the requirements for the functionality of the created object, CEUR Workshop Proceedings 2711 (2020) 161–175. URL: http://ceur-ws.org/Vol-2711/paper13.pdf.

[30] Polozhennia pro dystantsiine navchannia zdobuvachiv vyshchoi osvity za dennoiu formoiu u donbaskii derzhavnii mashynobudivnii akademii v osoblyvykh umovakh, 2020. URL: http://www.dgma.donetsk.ua/docs/acts/%D0%9F%D0%BE%D0%BB%D0%BE%D0%B6%D0%B5%D0%BD%D0%BD%D1%8F_%D0%BF%D1%80%D0%BE_%D0%94%D0%B8%D1%81%D1%82%D0%B0%D0%BD%D1%86_%D0%BD%D0%B0%D0%B2%D1%87_%D0%B2_%D0%BA%D0%B0%D1%80%D0%B0%D0%BD%D1%82%D0%B8%D0%BD.pdf.

[31] A. F. Tarasov, I. A. Getman, S. S. Turlakova, I. I. Stashkevych, S. M. Kozmenko, Methodical aspects of preparation of educational content on the basis of distance education platforms, CEUR Workshop Proceedings 2643 (2020) 161–173. URL: http://ceur-ws.org/Vol-2643/paper08.pdf.

[32] D. Y. Mikhieienko, Introduction of the use of cnc machine in teaching the discipline of computer design technology, in: Automation and computer-integrated technologies in production and education: state, achievements, development prospects, Cherkasy, 2020, pp. 263–264. URL: https://conference.ikto.net/pub/akit_2020_16-22march.pdf.

[33] D. Mikhieienko, The use of additive technologies in the educational process of the department of computer information technologies, in: Modern education - accessibility, quality, recognition, DSEA, Kramatorsk, 2020, pp. 109–111.

[34] P. Rocha, E. Tostes, Development of an embedded CNC control system, in: 2018 13th IEEE International Conference on Industry Applications (INDUSCON), 2018, pp. 407–412. doi:10.1109/INDUSCON.2018.8627296.

[35] B. Savant, R. Desai, Deployment of RTLinux on various platforms, in: 2007 IET-UK International Conference on Information and Communication Technology in Electrical Sciences (ICTES 2007), 2007, pp. 1058–1062.

[36] C. Liu, P. Jiang, W. Jiang, Embedded-web-based remote control for RepRap-based open-source 3D printers, in: IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society, 2017, pp. 3384–3389. doi:10.1109/IECON.2017.8216573.

[37] S. Zhang, Z. Sun, J. Long, C. Li, Y. Bai, Dynamic condition monitoring for 3D printers by using error fusion of multiple sparse auto-encoders, Computers in Industry 105 (2019) 164–176. doi:10.1016/j.compind.2018.12.004.

[38] A. E. Kiv, O. Merzlykin, Y. O. Modlo, P. P. Nechypurenko, I. Y. Topolova, The overview of software for computer simulations in profile physics learning, CEUR Workshop Proceedings 2433 (2019) 352–362.

[39] P. Nechypurenko, T. Selivanova, M. Chernova, Using the cloud-oriented virtual chemical laboratory VLab in teaching the solution of experimental problems in chemistry of 9th grade students, CEUR Workshop Proceedings 2393 (2019) 968–983.

[40] P. Nechypurenko, O. Evangelist, T. Selivanova, Y. O. Modlo, Virtual chemical laboratories as a tools of supporting the learning research activity of students in chemistry while studying the topic “Solutions”, CEUR Workshop Proceedings 2732 (2020) 984–995.