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INNOVATIVE METHODS OF USING PHYSICS LABORATORIES IN MECHATRONICS EDUCATION

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Abstract
Laboratory-based learning plays a crucial role in mechatronics education, enabling students to integrate theoretical knowledge with practical engineering skills. However, traditional physics laboratories face significant challenges, including high equipment costs, limited accessibility, infrastructure constraints, and difficulties in serving large student cohorts. This paper examines innovative methods of using physics laboratories in mechatronics education, focusing on virtual laboratories, remote (IoT-based) laboratories, augmented and virtual reality (AR/VR) technologies, and digital and mobile laboratory tools.

Based on an analysis of international research findings, project reports, and practical implementations, the study highlights how these innovative approaches enhance learning outcomes, student motivation, and engagement while improving resource efficiency. Meta-analytical evidence indicates that virtual laboratories significantly improve students' academic performance and motivation, while remote laboratories provide real-time access to physical equipment regardless of geographical constraints. AR/VR-based laboratories offer immersive learning environments that support safe experimentation with complex or expensive systems, while mobile laboratories that use smartphone sensors promote cost-effective, accessible experimental learning.

The paper also discusses the advantages and limitations of these methods, emphasizing that innovative laboratories should complement rather than replace traditional hands-on experiments. The findings suggest that a blended approach—integrating classical physics laboratories with digital, virtual, and remote components—is the most effective strategy for preparing mechatronics students for modern engineering and Industry 4.0 requirements. Recommendations are provided for the phased implementation of innovative laboratory practices in higher education institutions, particularly in the context of developing countries.

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Keywords: Mechatronics education; physics laboratories; virtual laboratories; remote laboratories; AR/VR technologies; digital learning tools; engineering education innovation; Industry 4.0.

Introduction

In multidisciplinary engineering disciplines such as mechatronics, laboratory training is a key component. Hands-on experience develops students' problem-solving, system design, and troubleshooting skills [1]. However, the introduction of traditional physics laboratories presents a number of challenges: expensive equipment, time-consuming and specialized infrastructure, and limited capacity for large student groups [2]. In recent years, new mechatronics programs and laboratories have been established in higher education in Uzbekistan (for example, 6 modern mechatronics laboratories were created in 5 universities within the framework of the MechaUz project supported by the European Union) [4]. In this regard, modernization of laboratory facilities and the introduction of advanced technologies are of urgent importance. Global experience shows that innovative approaches to using physics laboratories - including virtual laboratories, remote (online) experiments, digital learning tools, IoT devices, and AR/VR technologies - can overcome these problems and improve the quality of education [5,6].

LITERATURE REVIEW AND METHODOLOGICAL APPROACHES

The following innovative methods are used in the organization of physics laboratories in mechatronics education:

Virtual laboratories and computer simulations: With the help of special software platforms, physics and engineering experiments can be modeled in a digital environment. Virtual laboratories are open to students 24/7, allowing them to conduct experiments, collect data, and analyze data without equipment [7]. For example, platforms such as Labster offer interactive laboratory simulations in electronics, automation, and robotics [8]. Studies show that engineering students who use virtual labs achieve higher learning outcomes than those who use traditional methods - in particular, virtual laboratories significantly increase student motivation and engagement in the lesson [5]. At the same time, in a virtual

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environment, students can repeat experiments many times without fear of making mistakes, which strengthens their practical skills.

Remote labs (IoT-based): In this approach, students have the opportunity to remotely control real physical equipment via the Internet. Special IoT platforms (for example, LabsLand) provide remote access to real laboratory equipment connected to the global network - in this case, the student conducts experiments not with simulations, but with real devices around the world. Remote labs serve as an alternative to or complement to traditional laboratories: for example, one expensive piece of equipment is installed at a university, and it can be shared online by students from several educational institutions at the same time. This allows for the joint use of expensive equipment between educational institutions and reduces laboratory costs. Thanks to remote labs, students can conduct experiments day and night, without restrictions on location and time, and immediately connect theoretical lessons with practical training. For example, during the COVID-19 pandemic, many universities have set up remote labs, allowing students to continue their hands-on learning even when campus labs are closed [6].

AR/VR-enabled labs: Using virtual reality (VR) and augmented reality (AR) technologies, students can experience a fully immersive experience in a simulated environment. VR labs allow students to feel as if they are in a real lab—for example, they can assemble a robotic device or control a physical process in a virtual environment, and make decisions as if they were working in an industrial or scientific laboratory setting. This method helps to make complex and abstract concepts "tangible." VR gives students the freedom to experiment safely with expensive or dangerous equipment—for example, they can test an expensive electric motor model in VR and learn how to "break" it without fear of misconfiguration. Research confirms that blended learning in mechatronics, enriched with VR, is more effective than traditional classroom-only training. The cost of VR devices has become cheaper in recent years, making it possible for even small-budget institutions to implement modern VR laboratories. AR technology, on the other hand, allows students to conduct experiments by overlaying digital data on real equipment, for example, by displaying physical process parameters in a live view, combining real and virtual environments.

Digital learning tools and mobile laboratories: In addition to traditional laboratory equipment, digital sensors, software devices, and even smartphones are now being used as innovative laboratory tools. For example, digital experimental stations such as NI ELVIS are widely used in education (NI ELVIS III devices have also been introduced in Uzbekistan as part of the MechaUz project). Also, the experience of conducting various physics experiments using sensors built into smartphones (accelerometer, gyroscope, magnetometer, etc.) is becoming popular. With the help of such sensors, which are available in every modern phone, students can measure and study topics such as motion, vibration, and magnetic fields using their mobile phone itself. For example, the Physics Toolbox mobile applications developed in the USA and the PhyPhox mobile applications created in Germany turn a phone into a small physics laboratory - an ordinary phone can be used as an easily accessible and economical learning tool. Such digital solutions integrate technologies familiar to students into education, increasing their interest in the lesson and helping them test theoretical knowledge in a real-life context.

RESULTS

The above-mentioned innovative methods are used worldwide and have yielded a number of positive results.

According to the results of a meta-analysis on virtual laboratories, virtual labs significantly improve student learning outcomes (Hedges' g effect size ~0.68). In particular, when virtual experiments were introduced, students' motivation and immersion in the learning process increased significantly - the motivation index was several times higher than in traditional groups. This indicates that virtual laboratory activities encourage students to acquire knowledge and skills in science with enthusiasm. At the same time, researchers emphasize that virtual laboratories cannot completely replace traditional "hands-on" experiments, but they have become an important tool that complements their shortcomings.

Remote laboratories have been widely implemented and are yielding effective results in many educational institutions. For example, dozens of universities and schools in Europe have established online connections to real-world physical equipment through the LabsLand network. At the University of Navarra in Spain, students sat in the auditorium and remotely programmed FPGA chips located elsewhere in real time via the LabsLand platform - achieving simultaneous integration of theoretical learning with practice. During the pandemic, remote automation laboratories were quickly implemented at universities such as the

Politecnico di Torino in Italy, allowing students to work with real equipment from home. Such experiments have confirmed that remote laboratories serve to ensure the uninterrupted continuation of the educational process in emergencies and create additional convenience for improving the quality of education in normal times.

VR technology is also showing its effectiveness in practice. As part of international projects such as ViMeLa (Virtual Mechatronics Laboratory), a virtual laboratory for studying electric motors using VR was created, which allowed mechatronics students to learn more effectively than in a traditional laboratory. In VR labs, students are free to do practical exercises that are usually impossible to do in real life due to risk or financial constraints, which has a positive effect on their creative thinking and initiative. For example, at the Turin Polytechnic University in Tashkent, information is provided about the launch of experimental lessons in robotics using VR technologies. AR technologies are being integrated into laboratory equipment at some universities, for example, by making hidden parts of mechatronic systems visible (the introduction of such an AR application was presented at a conference at the Andijan Institute of Mechanical Engineering).

The results of digital and mobile laboratory tools are also important. For example, the "Physics with Phones" program, developed in the USA and Europe on the use of smartphones, has reached thousands of students and dozens of schools and colleges have allowed students to perform physics experiments using their personal phones, even if they lack laboratory equipment. This approach increases students' interest in real-life experiments and helps them "see" abstract concepts with their own eyes. Also, using digital sensors and platforms (for example, IoT-based remote temperature, pressure, voltage measurement systems), some universities are also instilling in students the skills to collect and analyze large databases - as a result, students are developing skills suitable for the modern Industry 4.0 environment.

DISCUSSION

The above innovative methods offer a number of advantages in mechatronics and physics education, but they are not without their limitations and disadvantages. They are analyzed below:

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Advantages:

Great convenience and freedom: Thanks to virtual and remote laboratories, students have access to the laboratory at any time, regardless of place and time. Remote technologies allow students to work with real equipment 24/7, making it easier to integrate practical training with theoretical classes. This creates equal opportunities, especially for students in remote or remote areas.

Resource efficiency: Thanks to virtual simulators and remote connections, a single laboratory device can be used by many students at once, which reduces the need to purchase new equipment. Different institutions can share expensive equipment online, which ultimately reduces the cost of building and maintaining a laboratory. Similarly, VR can create a virtual copy of expensive equipment, allowing institutions with small budgets to implement practical experiments.

Increased motivation and engagement: Interactive virtual environments, exciting visual effects of AR/VR, and innovative approaches in remote labs make the learning process more engaging and interesting for students. Research shows that such methods encourage students to actively participate in science, increasing their desire to independently expand their knowledge. For example, students who experimented in a VR environment were found to work more actively with greater enthusiasm and without fear of making mistakes than those in traditional labs.

Safety and risk-free experience: In virtual and AR/VR labs, students can safely try out processes that are considered dangerous in the real world. These methods "allow" students to experience situations such as misconfiguration and breakage of equipment, without damaging the equipment or injuring students. As a result, students learn by seeing various "unpleasant" situations, which strengthens their problem-solving skills. Virtual experiments also allow for testing many scenarios (e.g., extreme parameters) that cannot be implemented in a laboratory environment due to limitations.

Large-scale data collection and analysis: Through digital laboratory platforms (IoT sensors, data recording systems), a detailed database of each student's experience is created. This creates additional opportunities for analyzing, evaluating, and improving the learning process. For example, through remote labs, teachers can monitor online at which stage students are struggling and provide them with individual support. At the same time, students acquire the skills to work with modern digital tools and adapt to the digitalized production environment of the future.

Limitations and problems:

Lack of real "hands-on" experience: Virtual or remote labs, no matter how useful, can be, but they cannot replace the experience of working directly with real equipment. In order for a student to be able to hold, connect, and mechanically assemble real equipment, traditional laboratory exercises are still necessary. Researchers caution that virtual labs cannot completely replace traditional labs - they are best used in combination with both. Also, in remote control, the student may not be able to fully experience the physical structure of the device and the effects of the real environment.

Simplification of reality: Simulations and virtual environments are built on certain models and assumptions. Some unconventional situations that the programmer did not foresee may not be reflected in the virtual experience. However, in a real laboratory, unexpected results or "quirks" of the equipment are sometimes observed - it is these subtle details that can be valuable lessons in engineering. Therefore, a student who works only in a virtual environment may miss some of the complexities of real life and may have difficulty in later production. Similarly, VR technology cannot yet fully imitate tactile (sensory) contact and the effect of physical force, which limits the development of some skills (for example, how to properly hold a tool, how to pull with force).

Technical infrastructure and costs: The introduction of innovation labs requires a certain initial investment - powerful computers, VR headsets, or a fast internet connection. This can be quite a challenge for some educational institutions, and especially for students. For example, high-speed internet is not available in all areas to use a high-definition VR system or a remote lab platform. Also, if many users want to use remote labs at the same time, there is a risk of server or hardware resources running out, which can cause queuing and latency problems.

Staff training and pedagogical acceptance: The training of teachers is of great importance for the introduction of new technologies into education. Unfortunately, many teachers still do not have experience in using these tools or are not aware of them. It is observed that some teachers who are accustomed to traditional methods find innovative tools interesting, but do not implement them in their lessons. The

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reason for this is that they do not have enough training, lack time, or fear of technical difficulties. Therefore, when introducing innovative laboratories, it is necessary to train staff, prepare methodological guidelines, and regularly monitor the effectiveness of these tools. Content and software problems: It is not easy to prepare high-quality digital content for virtual and AR/VR laboratories that is consistent with the curriculum. It takes time and money to create such programs, and in some cases, if there is not enough ready-made virtual training, the educational institution will have to develop it itself. There are also issues of compatibility between different platforms, software bugs, and updates. If the system fails, the entire learning process can be disrupted – so it is always important to have a backup plan, such as the ability to revert to the traditional method.

CONCLUSION

In conclusion, innovative methods of using physics laboratories in mechatronics education open up wide opportunities for educating students at the level of modern requirements. The virtual laboratories, remote experiments, AR/VR technologies, and other digital tools discussed above are proving their advantages in terms of improving the quality of education, increasing student activity and interest, as well as efficient use of resources. World experience has shown that by introducing such innovations, it is possible to prepare a new generation of engineers to solve modern technological problems. At the same time, it is inappropriate to contrast traditional and innovative approaches - scientific research and practical results have confirmed that their integration is the most effective way. By enriching classical physics laboratories in mechatronics education with virtual and remote components, students will have the opportunity to consolidate theoretical knowledge in real and digital environments. The recommendation for higher education institutions in Uzbekistan is that the introduction of these innovative methods should be carried out in a phased and well-planned manner: first, improve the skills of personnel, prepare the material and technical base, and then introduce selected technologies into the educational process on a trial basis. This will raise the practical training of mechatronics students to a new level, ensuring that they acquire knowledge and skills at the level of today's rapidly changing scientific and industrial requirements.

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