Cross Reality Spaces in Engineering Education

Online Laboratories for Supporting International Student Collaboration in Merging Realities

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Abstract—This paper discusses online laboratories as cross reality spaces in education. Cross Reality (also XR) as a term is borrowed from the field of gaming and broadly describes the integration of immersive, augmented, mixed, and virtual reality technology within physical reality. Online laboratories form an ideal example, as different realities (the real hands-on world in real labs, the virtual world in simulated labs or even a mixture of both in context with remote labs) are merged. The connection between different realities in laboratory education and their relation to engineering education contexts are discussed by describing a three-dimensional matrix for categorizing (online) laboratories in teaching and displaying current research results in this area. On basis of this, a scholarly research study is discussed, which is making use of a remote lab in mechanical engineering education for an international student body. In this study, the lab and its application are evaluated from the learner, the system, and the course perspective. These three perspectives offer a holistic view of the lab and the students' learning. The study proofs a positive effect on the students learning experiences. The results also show which current needs and future potentials lie on the intersection of engineering education, internationalization, and digitalization in terms of collaborating and learning in Cross Reality Spaces.

Keywords—Engineering education, online learning, online laboratories, cross-reality spaces, internationalization

1 Introduction

Since digital technologies found their way into higher education institutions, there have been discussions about whether the increasing digitalization might be a threat to the physical nature of universities and educational quality [1]. Especially when massive open online courses (MOOCs) became popular around 2012, skepticism arose around the didactical quality of online teaching in higher education [2]. However, from the very beginning digitalization has offered new promises as well as challenges for educational practice. Specifically, in the era of ongoing internationalization in the educational sector digital technologies offer new pathways for fruitful collaboration and communication. The described work displays such an example from the educational practice and research perspective. This study shows how digital technology in the area of laboratory learning can help to bring international engineering students together with the opportunity to work as worldwide distributed teams, just as it is common in industry.

2 Background: Cross Reality Spaces in Engineering Education for online engineering and learning

Just as digital technologies already form everyday communication and international collaboration in engineering practice, online engineering will be a focal area of research and development for the internationalization of higher engineering education research. Such development is geared towards overcoming the gap between the highly internationalized professional field of engineering and the corresponding field of education, which is not as internationalized when it comes to actual international collaboration between students. The following paragraphs will discuss emergence of online engineering in its various forms. In this context, tele-operatively or virtually executing engineering experiments are of high interest and can serve as an example application for a new way of learning in Cross Reality Spaces, which embraces different forms of virtual or mixed reality.

2.1 Online learning in engineering in cross reality spaces

Looking at higher engineering education research, the development of online engineering has gained importance over the last decades. Following the International Association of Online Engineering (IAOE), this field covers working directions such as remote engineering, cyber-physical systems, virtual instrumentation, and simulation technologies. Within these working directions, good progress has been made in order to make engineering equipment accessible for teaching and learning contexts, either using virtual, augmented or remote technology ([3] - [10]).

Remote, augmented or virtual laboratories (see the following sections for further details), for example, offer opportunities for building international student working groups in engineering across institutional, time, and even cultural borders [11]. Nevertheless, this progress and its potentials for the transformation of everyday teaching and learning practices in engineering needs a profound conceptualization with regard to technical, social and didactical consideration. There is still a detectable lack in the question of empirical grounding for using such technologies within education contexts. Many studies so far remain on the level of technical considerations or student satisfaction, but they do not go beyond. More specifically, these studies compare real, remote accessible, or virtual instrumentation by looking at their impact on learning and communication practices or sociotechnical issues. Furthermore, the debate around globalization in higher education practice combined with online engineering technologies has not yet been discussed sufficiently.

Online Engineering in the context of education can also be seen as an example of learning in Cross Reality Spaces. For the increasing fusion of interaction (and learning) in offline and online spaces, [12] formed the conception of teaching and learning in CrossActionSpaces. This idea bases primarily on the constant availability of information through the Internet and how that shapes interaction, especially when it comes to learning. However, in context with learning in and with virtual reality applications, that concept seems to be not sufficiently descriptive, even though great similarities can be stated. In relation to engineering experimentation and questioning whether an experiment is done on-site, it can be argued that learning happens in Cross Reality Spaces with the help of tele-operative equipment, augmented reality, or full simulation. The term Cross Reality (also XR) is borrowed from the field of gaming and broadly describes the integration of immersive, augmented, mixed, and virtual reality technology within physical reality [13]. Remote laboratories form an ideal example. They are built of real equipment and give out real data, but they are used tele-operatively over the Internet, meaning that the actual user interface can be seen as a virtual reality merging with the real world. With ongoing research and development in the area of online engineering, it becomes technically more and more exchangeable whether an experiment is done in an on-site lab, in any kind of digital environment, or in a mixture of both. The future important issue will be choosing between these options and determining how much the one or the other option affects the learning process and outcome. Hence, it is much more a pedagogical rather than a technical consideration. Thus, the combined view on virtual reality and experimentation has the potential to open a new area of interdisciplinary research on learning in Cross Reality Spaces.

2.2 The online laboratory in engineering education

The significance and aim of the format laboratory in engineering education is described by [14] as follows:

> *The use of laboratories is essential for the education in engineering and science related fields at a high qualitative level. Laboratories allow the application and testing of theoretical knowledge in practical learning situations. Active working with experiments and problem solving does help learners to acquire applicable knowledge that can be used in practical situations. That is why courses in the sciences and engineering incorporate laboratory experimentation as an essential part of educating students (ibid. S. 285).*

This results in a two-fold motivation for the use of laboratories in teaching. On the one hand, it is about applying theoretical knowledge, comparing mathematical models with reality, recognizing familiar relationships and phenomena, and finally understanding them in the context of practical activities. On the other hand, laboratories also offer the possibility of acquiring practical skills and generating new knowledge through self-guided independent research action. [15]

[15], however, show that despite the laboratory's great importance and tradition as a teaching-learning format in engineering education, a comprehensive didactic analysis of this has so far scarcely taken place (ibid., p 17 f.). Central scholarly discussions

with the laboratory as a conceptual learning place in engineering education in the German-speaking world exist only in publications of [16], [17], and [18] and are therefore an exception. Based on these, more detailed studies have been developed in recent years, mainly by the work of [19], [8], [20], and [15]. These studies put a special focus on metal forming technology and substantially expanded the body of knowledge by new research results.

2.3 Online laboratories framework along the degree of virtualization and educational approach

For the didactic classification of educational laboratories, different models can be identified in literature, but they all make a classification along the students' degree of freedom during the experiment. Thus, [17] distinguish three stages of laboratory work ([21] and [7] show similar approaches):

- **Level 1:** *Practical experiments* according to rigid and pre-defined rules and regulations.
- **Level 2:** *Practical (possibly open ended) experiments* with several variations in the experimentation sequence
- **Level 3:** *Independent scientific work* using laboratory equipment and following general scientific procedures (e.g. in the context of final examinations)

Another pattern for distinguishing educational laboratories is shown in [15] on the basis of [22]. It describes different degrees of openness as:

- *Confirmation labs* follow the goal of guided understanding of previously known theories, principles and concepts. The students' task is to verify these along clearly defined working steps.
- *Structured inquiry labs* also include a pre-structured process, which the students follow along a structured task. However, the result is not necessarily known here before.
- *Guided inquiry labs* enable the students to work on a given task as independently as possible. They are only accompanied by the teacher.
- *Open inquiry labs* describe the use of laboratory equipment in the context of the students' research activities. They are supported by the teacher but are largely free with regard to the definition of a research question, the chosen course of action, the data evaluation, and the subsequent modeling.

From a technological perspective, laboratories can also be distinguished with regard to the type of man-machine-interaction, the type of experiment's equipment (real experiment or simulation), and the experiment's or user's location during the experimentation process (being at the same or at different places) ([23] and [24]). Hence, educational laboratories can be differentiated into three basic types ([25] and [20]):

- The *real on-site laboratory* is the classic version of a laboratory experiment in which the students perform experiments directly at the test stand.

- The *remotely controlled real laboratory* also relies on physically existing equipment for carrying out the experiment. However, here the users and the equipment are not in one location but are connected via the internet. The experiment is carried out remotely and the measurement data is transmitted via the data connection too.
- The *simulation as a laboratory* describes the completely virtual execution of experiments, which are also usually performed on the computer. Here, no real tests take place, but all conceivable input variables, their combinations, and the results are stored in preconfigured algorithms.

In addition, there are also many thinkable and documented hybrid lab forms (see [24]). By combining both the educational practice and technological implementation perspectives, a 2-axis matrix for categorizing laboratories can be created (Figure 1).

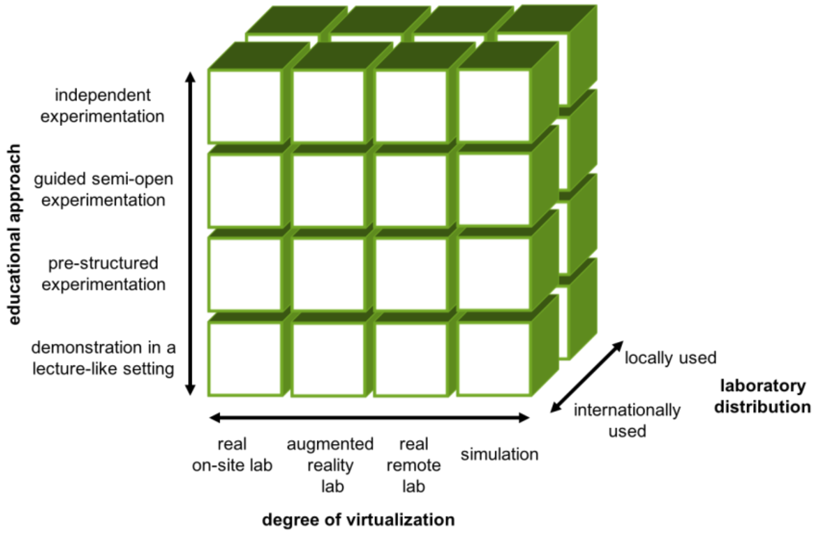


Fig. 1. Three-dimensional matrix for categorizing the use of laboratories in teaching along the degree of virtualization, the educational approach and the laboratory distribution

The technical differentiation is made along the degree of virtualization. In addition to the above-named levels, a fourth group is included to represent laboratory applications making use of augmented reality technology. The didactic dimension distinguishes between the above explained levels 'demonstration in a lecture', the 'pre-structured experimentation' (mostly under clearly defined framework conditions and, if necessary, with known results), the 'guided semi-open experimentation', and 'independent experimentation'. In addition, this model offers the possibility of supplementing further descriptive dimensions. For example, a distinction can be made as to whether the experimentation takes place in a team or in individual work, or, as shown in the picture, if it is embedded in local teaching and learning contexts or in international course settings. The example explained later on in this chapter will show the combination of a guided semi-open experiment, which uses a remote lab equipment, and addresses internationally users.

2.4 Putting online engineering education into practice

Although there is much room for debate on the progress concerning digitalization and internationalization in engineering education, there are undoubtedly efforts and projects described in literature showing the current best practice examples of online engineering education efforts with remote laboratories and internationalized engineering education using digital technology. Such projects will be briefly explained in the following to form the background for further considerations.

The scientific discourse, which includes the research and development around virtual, augmented, and remote laboratories, is internationally driven by the International Association of Online Engineering (IAOE), the Global Online Laboratory Consortium (GOLC) and the Experimentation and Laboratory-Oriented Studies Division of the ASEE. Relevant publications can also be found in the International Journal of Online Engineering (iJOE) and in the proceedings of the International Conference on Remote Engineering and Virtual Instrumentation (REV), the ICL-International Conference on Interactive Collaborative Learning (ICL) or the Experiment@ International Conference (Exp.At). The projects described in the following show current best practice and state-of-the art in this area of research:

- As part of the EU-*funded Go-Lab project*, a multitude of virtual and remote laboratories from all STEM areas and across several countries are bundled in one platform [26]. This was intended primarily to reach schoolchildren from the countries of the participating project partners, in order to inspire them for technical topics and to offer the possibility for a more self-directed learning. Building on the developed infrastructure, the follow-up project NextLab has been launched in 2017. This project bundles more than 500 different virtual laboratories, remote laboratories and apps in the same way.
- The *VISIR+ project* focuses on the field of electrical engineering and connects 12 international universities in the development of real, virtual and remote laboratories. In the context of the VISIR laboratory developments, the qualitative and quantitative evaluation of the included laboratories is increasingly becoming the focus of attention [27].
- Similarly, [28] describe the development of a remote laboratory in the field of electrical engineering. While the lab provides an automated tutor during the experiment to assist the students during the experiment, the interface also offers the possibility for several students to simultaneously access the experiment. Consequently, the group's digital link permits them to evaluate and discuss the experiment. This approach describes one of the few globally existing approaches to link remote laboratories and virtually networked teamwork.
- As part of the *ELEOS project*, an international online program on the Bachelor level in Electronics and Optics for Embedded Systems has been developed for international distribution (see [29] and [30]). The aim of this project is also to include

the usage of tele-operative laboratories (in the Fields of physics, chemistry and mechanics) in online education so that engineering courses can be completely delivered online on the long-term. For course distribution, both synchronous and asynchronous teaching and communication tools are used and tele-operative laboratories are added to the system.

Furthermore, there is a large number of research initiatives worldwide in the area of virtual and remote laboratories. For a broad overview see e.g. [3] - [10].

The above-mentioned projects and the literature illustrate two key aspects that underpin the necessity of further research on online experimentation and internationalization. On the one hand, there is an overhang of offered laboratories in the field of electrical engineering and information technology, although research and development in online engineering is not restricted to a specific discipline in the field of engineering. In contrast on the other hand, there are only a few examples in the field of mechanical engineering that go beyond simulations and offer remote tests with real existing equipment. In addition, there are hardly any examples which exploit one of the central advantages of the virtual and remote laboratories: The global accessibility of online engineering technologies, e.g. for using them in international online courses (with the exception of the ELEOS project). The following sections consider the existing achievements as well as limitations and presents an example of educational practice on the intersection of digitalization and internationalization through online engineering in engineering education.

On basis of these theoretical considerations, this chapter will apply the theory by discussing a study which makes use of online engineering technology in context of international educational practice. The context is an online class that addresses an international mixed student group and makes use of remote laboratory equipment ([11] and [31]).

3 Study: Using remote laboratories for international online learning groups

So far, international learning experiences using online communication tools are mostly limited to the development of professional competences, such as interpersonal communication, team work abilities, or intercultural sensitivity. That observation can easily be proofed by looking into the work of [32] – [36], who offer an in-depth synopsis of the discussion around international engineering education. Nevertheless, engineering education also needs technical education, which can be achieved through the integration of laboratories into the curriculum. Online engineering technology, or better remote laboratories, now opens up experimentation processes to groups of students, who do not necessarily need to be at the same place while performing experiments together. This means to include both technical education and social interaction through online communication in the same activity. The following example will show a case of educational practice in such a context.

3.1 The course context

With the Master of Science in Manufacturing Technology (MMT), the Faculty of Mechanical Engineering of TU Dortmund University (TU Dortmund) has been offering an English-language Master's degree in Production Technology since 2011. This program addresses students with a Bachelor's degree from all over the world and brings a very international mixed group of students to Dortmund each year. In order to prepare the MMT students for their time in Germany, an online course has been developed and offered in advance of their stay. It turned out that in many cases the students take part from their home country before travelling to Germany. The course offers a diverse set of learning activities and already has been described with detail in literature ([11] and [31]). For this chapter the remote laboratory's integration into the overarching course concept is of focal interest. That integration put engineering theory and practice into the course concept and offer the possibility to work together with worldwide distributed fellow students on core engineering tasks, such as engineering experiments. The following part gives a brief description of the equipment.

3.2 The remote laboratory and course equipment as educational tool

The developed remote laboratory was a central instrument for linking theory and practice throughout the online course. It represents a tele-operative testing cell for material characterization in the field of forming technology and has been developed at the Institute of Forming Technology and Lightweight Components (IUL) in close cooperation with the Center for Higher Education at TU Dortmund University. With the remote laboratory, students can perform real-physical experiments remotely over the Internet without having to be present in the lab. The lab's original development refers back to the international research project "PeTEX - Platform for E-Learning and Tele-Experimentation", in which pioneer research and development for setting up and using tele-operative laboratories in forming technology was conducted ([8], [19], and [20]).

Currently, the testing cell consists of two testing machines (one universal testing machine Z 250 from Zwick/Roell (pictured right) and one BUP 1000 sheet metal testing machine from Zwick), one robot (KUKA KR 30-3) for material handling and several IT components (Figure 2). Both machines are automated for tele-operative use. Thus, an interdisciplinary laboratory has been set up to include aspects of robotics, measuring, and energy technology.

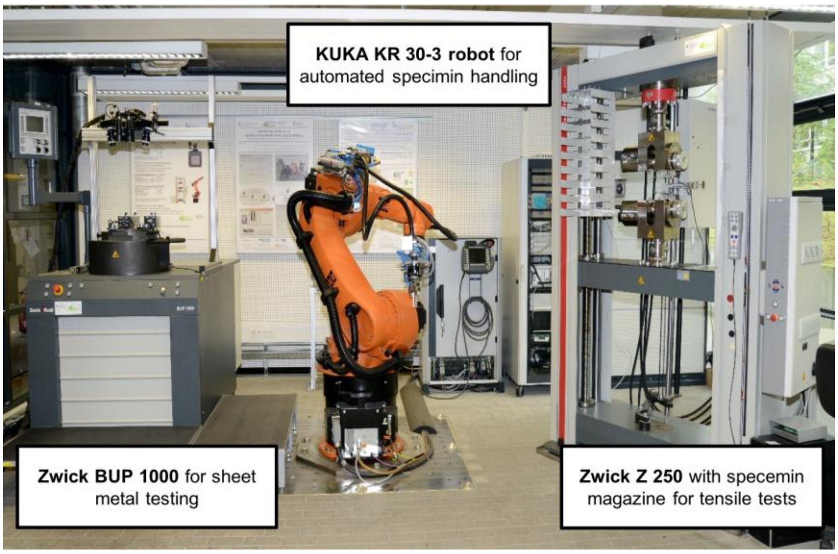


Fig. 2. Tele-operative testing cell at the IUL in the current expansion stage with two testing machines and one robot for automated test specimen handling

For the tele-operative execution of experiments, a graphical web interface was developed and integrated into the existing iLab architecture for online experiment facilitation [37]. This interface provides access to the testing equipment via a computer using Internet connection. Through that connection it is possible to reserve a time period for experimentation, carry out the actual experiments, and download the generated data. The web interface can be subdivided into four different interaction areas fur the user (Figure 3):

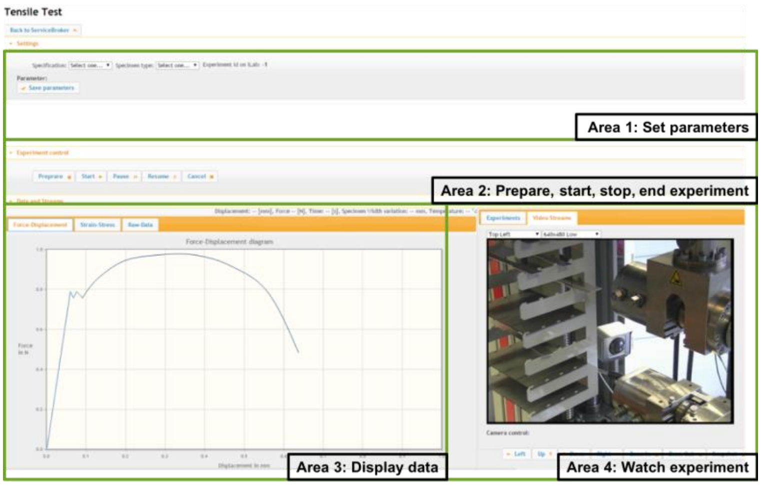


Fig. 3. Graphical web interface for operating the testing cell

- Area for setting test parameters: Selection of different test parameters for the experiment to be performed (e.g. strain rate or test specimen to be tested) have to be made here.
- Area for preparing, starting, pausing, and canceling: Interaction between user and test equipment takes place here. The user can then start, pause or cancel the experiment. For preparation, the robot places the desired specimen in the testing machine.
- Area for data acquisition: The obtained data (applied force on the sample as well as the technical elongation of the sample) is presented here in real time, in either numerical form or alternatively in the form of a force-displacement diagram or as a stress-strain diagram.
- Area for equipment observation: A live video stream can be displayed here and it can be selected from various camera perspectives (e.g. close-up of the test specimen or the test setup in the long shot).

After the successful completion of an experiment, the test is automatically terminated. The robot removes the used test specimen from the machine, and the system returns to its initial status so that a new experiment can be carried out. The data obtained is automatically stored in the system in order to download it.

In the following, the course context in which this laboratory is used will be explained more in detail.

3.3 Educational intervention using online experimentation

Knowing material characteristics is of high importance for component design tasks in engineering. Being able to use experiments for gaining such data is a focal learning goal in mechanical engineering education and, hence, in the described online course too.

For the determination of material characteristics, the students remotely use the IUL's tele-operative testing cell and carry out uniaxial tensile tests. First, the students conduct preparatory research on the basics of uniaxial tensile testing, force-displacement diagrams, and stress-strain diagrams. Based on that, the students then use the tensile test in the tele-operative testing cell to determine the stress-strain curves and the material characteristics for a steel material (DC04) and an aluminum material (AlMg3). On basis of the test results, they finally design a component for a car body while considering a given force acting on the component.

For the actual remote experiment, small groups are formed in which the students jointly carry out the experimentation procedure. For this purpose, the groups organize themselves and book their time slot for using the testing cell. Finally, the group members meet in an Adobe Connect online conferencing room to conduct the experiments. One student also logs in to the experimentation web interface and shares the screen with the other group members. In this way, all group members can watch the experiment, communicate, and interact among each other through Adobe Connect. Each group member should carry out at least one experiment with each of the materials and freely choose the test parameters from a pre-set range. Once one of the members successfully completes these experiments, he or she logs out of the experimentation environment and gives someone else the opportunity to share the screen. In this way, each of the group members performs at least two experiments with the tele-operative testing cell. Figure 4 shows a screenshot during the execution of such an experiment. Using the obtained material parameters, the student groups solve a given the given task on component design.

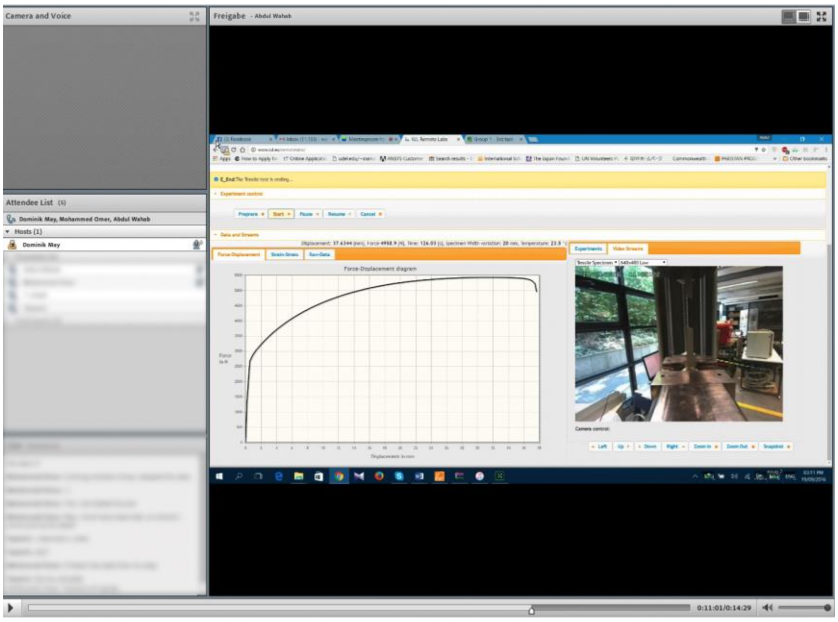


Fig. 4. Screenshot during the execution of a tensile test by students

4 Results: Remote laboratories for International Online Learning Groups

As the overarching course concept focused on more than online experimentation, a holistic evaluation concept with focus on competence development, internationalization, and theory-practice-integration has been developed and implemented [31]. The remote experimentation part of the course falls into the evaluation focus in theory-practice-integration. For this focus, adequately suitable existing questionnaires could not be identified the literature. Therefore, an individual instrument was developed ([38] and [39]).

4.1 Evaluation concept

For the laboratory evaluation, three different evaluation perspectives were selected and considered separately (Figure 5). These perspectives were the learner perspective (students' competence development during the experimentation process), the system perspective (functionality of the used technical equipment) and the course perspective (experiment's embedding in the didactical and content-related course context).

Fig. 5. Perspectives for the holistic evaluation of experiments in engineering education

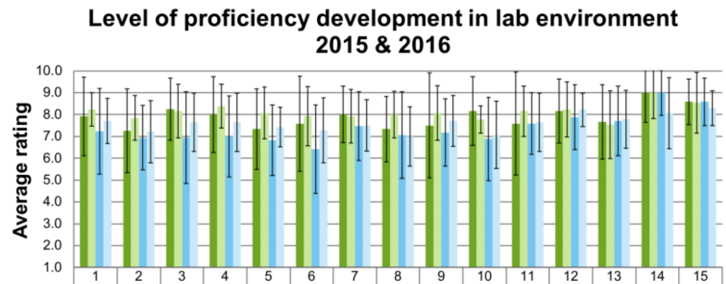
Fitting survey questions were developed for all three sections. For the learner perspective, reference was made to the work of [21] and [40]. [21] Defined 13 learning outcomes that should be pursued while using engineering laboratories in teaching. These learning outcomes were rephrased and transformed into 15 statements, on which respondents should assess their own ability and level of proficiency on a 10-point Likert scale from "low level of proficiency"(1) to "high level of proficiency"(10). This questionnaire was used in form of a analysis before and after the experimentation task. For the system and the course perspectives, a joint questionnaire was developed with significantly influence from the work of [25], [41], [42], and [43]. Based on this, 5 categories (platform and device, laboratory system, experimental instructions, test procedure, and general evaluation) were defined and 20 items were developed. Each item was represented by a statement and the respondents were asked to indicate their agreement from "strongly disagree"(1) to "strongly agree"(5) along a 5-point Likert scale. For an in-depth evaluation, the questionnaires were supplemented by course internal feedback opportunities and observations (with the help of video caption) by the teacher during the actual experimentation process [44].

4.2 Evaluation results

The evaluation results refer to the course editions in summer 2015 and 2016. In total, 36 students from 14 different countries (South Korea, China, India, Iran, Pakistan, Sri Lanka, Nepal, Syria, Turkey, Tanzania, Spain, Tunisia, Mexico, and Colombia) took part in these two course editions. The age structure was the following: 10 students were at the age between 20-22 years, 19 at 23-25, 3 at 26-28, 3 at 29-31, and 1 over 31 years. Except for 4 students, most of them already had international experience because of an international cultural background or because of friends or stays abroad. Even though all of the students graduated in mechanical engineering (or a closely related field), none of them had used a virtual or remote laboratory before.

Learner perspective: Figure 6 shows the results of the pre-post-survey regarding the learners' perspective on their own proficiency development from 2015 and 2016. The item numbers in Figure 6 refer to the items shown in Appendix A.

The results show that based on the students' self-assessments for most of the considered items, a positive development can be observed (in 2015 a positive development is visible in 9 and in 2016 even in 12 of the 15 items). Items 1, 2, 4-6, 9, 11 and 12, in particular, show an increased perceived ability level in both years. Under combined consideration of both years, items 4-6 and 9 are noticeable since an increase of 0.5 points can be seen for each of the items. On this basis, it can be stated that the experiment carried out remotely on the course can have a positive influence on the competences in dealing with test data (items 4 and 5), the use of test results for concrete application contexts (item 6), and the application of experiments and their results in the larger context (Item 9). On the other hand, the most significant drop in the rating can be seen in Item 14 (working effectively in a team). One reason for this could be that the laboratory and web interface itself in its current setting is not directly suitable for working in teams and, consequently, Adobe Connect is necessary as a detour. Statements by students support this assumption.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Pre-Test 2015 (N=12)	7.9	7.3	8.3	8.0	7.3	7.6	8.0	7.3	7.5	8.2	7.6	8.2	7.7	9.0	8.6
Post-Test 2015 (N=13)	8.2	7.8	8.2	8.4	8.1	7.9	7.9	8.0	8.1	7.8	8.2	8.2	7.5	9.0	8.5
Pre-Test 2016 (N=17)	7.2	6.9	6.9	7.0	6.8	6.4	7.5	7.1	7.2	6.9	7.6	7.9	7.7	9.0	8.6
Post-Test 2016 (N=14)	7.7	7.2	7.6	7.6	7.4	7.3	7.5	7.0	7.7	7.1	7.6	8.2	7.8	8.1	8.3

Fig. 6. Respondents' assessments of their own level of proficiency with respect to 15 key activities in the laboratory (with 1 = "low level of proficiency" to 10 = "high level of proficiency"; for item numbers see Appendix A)

In addition to the numerical assessment, the students were asked to assess how far they perceived the development of their own abilities as fallen, unchanged, or increased. The results are shown in Figure 7. Items 5, 8, 10, 11 and 15 stand out negatively in this context, as less than two-thirds of the respondents perceived a positive development here. However, this can also be due to a high initial level, which makes further positive development more difficult. In other words, a positive conclusion can be drawn in that for 10 of the 15 items over two-thirds of the students perceived an increased ability level.

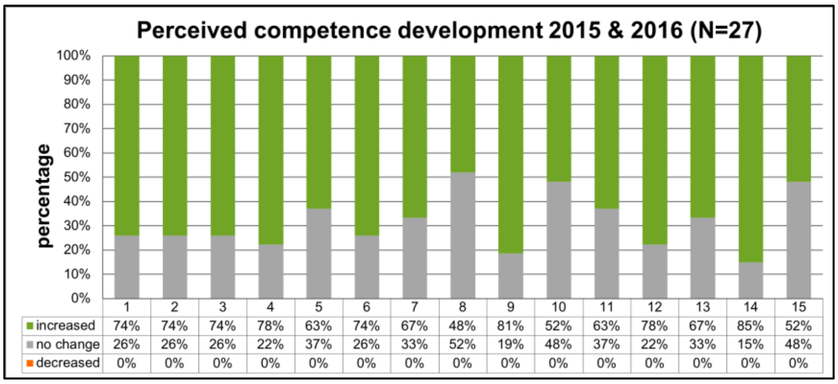


Fig. 7. Respondents' assessments of their perceived development with respect to 15 key activities in the laboratory (with 1 = "strongly disagree" to 5 = "strongly agree"; for item numbers see Appendix A)

System and course perspective: The system and the course perspective were examined with separate questionnaires. Appendix B gives an overview of the items used here and assigns the items to the respective numbers used in Figure 8.

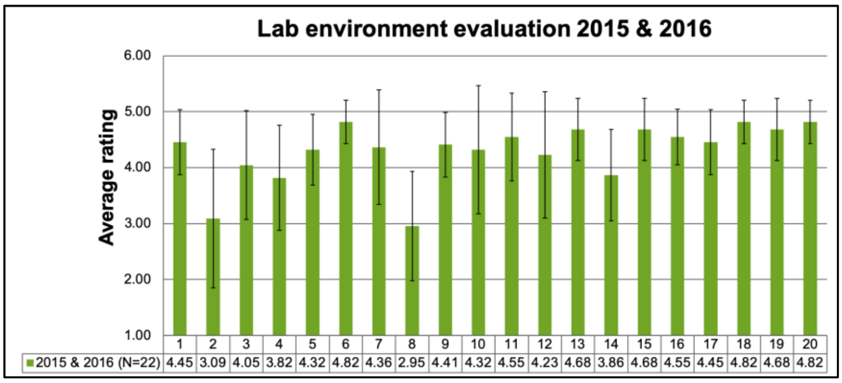


Fig. 8. Assessment of the laboratory environment with respect to system perspective (items 1-5), course perspective (items 6-15), and an overall evaluation (items 16-20) (with 1 = "strongly disagree" to 5 = Strongly agree; for item numbers see appendix B)

It becomes clear that the results for the system perspective (items 1-5, and especially 2-4) are comparatively low. This can be explained by observations made during the experiments. On the one hand, there were problems with the equipment in both years. Not every experiment initiation in the web interface led to a successful experiment in the laboratory. In some cases, the server lost connection for no apparent reason. In other cases, the bandwidth, which was required for the experiment, could not be ensured by all students. There were additional problems, especially in 2015, with the combined use of the web interface in iLab with Adobe Connect and the desktop sharing feature. Here, splitting the screen meant that the user web interface became inaccessible and therefore an experiment could not be started. This problem could be observed more often using the Firefox Internet browser and less frequently seen in combination with the Chrome browser. These and other system stability issues can be seen as justification for relatively low outcomes of the system perspective and suggest potential for improvement.

In total, 73 attempts for experiments were initiated by students in 2015 and 2016. 40 were successfully completed, and the students used the data for the task's completion. In 33 cases, the experiment was canceled for a variety of reasons. This corresponds to a quota of 45% failed and 55% successful experiments. The examination of the videos shows a heterogeneous picture for different reasons. In addition to the above-mentioned problem of overlaying the user interface by Adobe Connect desktop sharing (7 cases), the following errors occurred and interrupted the experiment: Errors in material handling by the robot (e.g. two samples taken at the same time or in an empty compartment in the sample magazine, 6 cases), server problems on the campus (9 cases), expiry of the booked time window for the experiment (2 cases), or insufficient bandwidth on the part of the student (1 case). In another 8 cases, no specific reason could be identified. In these 8, the experiment was terminated independently by the system and the test results could not be saved.

On the other hand, fairly good results for the course perspective in items 6-20 could be achieved. That result speaks for a positive feedback on the experiment's integration into the course concept and the learning experience. Items 16-20 were rated especially high with an approximate average of 4.5 points. This positive result is further strengthened by the fact that over 80% of the respondents, asked for their rating of the online experiment on a scale of 0 = "very poor" to 10 = "very good", rated the experience with an 8, 9 or 10.

Conclusively, a positive conclusion can be drawn for the remote lab's integration into the course. On the one hand, the tele-operative testing cell made it possible to successfully integrate real-world engineering experiments from the scientific field of metal forming into the transnational online course. Furthermore, the students were able to apply the associated theories in realistic contexts on the basis of the assigned task to perceive the significance of experiments. The results show that there is still room for improvement in terms of both technical system stability and the possibility for experimenting jointly in distributed teams. However, no further serious problems are attested. On a positive note, competence development has been proven by using a pre-post analysis and has been reported by the students in additional informal discussions after the course. This conclusion is also supported by the results of the program internal review elements, such as written student reports or participatory observation.

5 Discussion

In summary, an evaluation of the results promotes a positive competence development in the area of executing engineering experiments. Despite the positive results that could be emphasized in the evaluation, some critical remarks and limitations should be discussed.

In some parts, the results show only a slight positive trend or even a slight decrease. This aspect is a clear limitation. Reasons for the results' lack of significance can be manifold. The reasons can be based on either a methodological aspect in the evaluation concept or a further lack of competence development for these explicit items. A further explanation of the partly negative values can be assumed on basis of the work from [45] and [46]. They discuss the reliability problems in context with learners' self-perception when assessing their own competence. According to this work, students tend to rate their own abilities too high before a didactical intervention, which may be also reflected in the presented study's pre-test results. After a learning experience, a more realistic self-assessment is possible, with the probability for ratings one's ability lower than before. In this specific case, the respondents in the pre-tests initially considered themselves to be more competent in experimentation than they really were. Through the remote laboratory activity, this assessment has been subjected to a reality check, and the post-test assessment was based on a more realistic view. This also means that despite the negative scale development between the pre- and post-tests, competence development may still have taken place. It is just not visible in the data as the development starts from a lower level than expressed by the pre-tests. The extent to which this effect is actually visible here cannot be conclusively answered at this point and remains pending for further investigation.

Another limitation is the small number of students participating in this study. This also has an effect on the results' validity. On basis of this study, it is not possible to make a clear statement as to what extend the developed approach leads to competence development for other target groups than the one considered here. Although the results obtained show positive tendencies in this context, they also form the basis for further summative investigations in which more valid results need to be achieved.

Despite the limitations that have to be stated, a positive picture still can be drawn. Since the course and the remote laboratory's integration must also be understood as a proof of concept, it can be stated, that he combination of online teaching for a worldwide distributed student group and the use of a tele-operative laboratory facility could be successfully implemented The evaluations and the consistently positive participant feedback show, that these and similar approaches offer great potential for the innovation and development of higher education in terms of digitalization in engineering education and internationalization.

Putting a special focus on the educational practice of online engineering and Cross Reality Spaces through the example of remote laboratories leads to several essential insides:

- Connecting international students with digital collaboration and communication tools enables the formation of transnational work teams and imitation of international work contexts.
- In the (remote) laboratory, engineering theory meets practice, while promoting the science- and practice-oriented education of engineers. Therefore, educational laboratories must be fitted with special care into the course setting and should not be considered separately.

- Especially for students from countries with low Internet access, all included digital tools should require as little bandwidth as possible and the course communication should be spread across several distribution channels.
- Tele-operative experimentation environments offer added value when the user interface also provides the opportunity for interaction between the experimenters. This should therefore be ensured.
- Tele-operative equipment offers the theoretical possibility of 24-7 availability; however, this requires robust system stability. This must be guaranteed (including in terms of test specimen supply) so that the promise of use anywhere and anytime can be kept. This also has a direct positive impact on the scalability of similar approaches.

The presented results show which current needs and future potentials lie on the intersection of engineering education, internationalization and digitalization in term of collaborating and learning in Cross Reality Spaces. Advancing globalization is simultaneously the trigger and the projection surface for necessary innovations. Sustainable implementation of an international and intercultural engineering education also offers universities the opportunity for distinctness in international competition for highly qualified students worldwide.

Further elaboration of reliable research results on competence development through internationalization and digitalization in the field of engineering education is therefore of particular importance, as only valid research results secure innovations' transferability from the specific case to other application contexts. Even if innovations achieved in a specific case are beneficial for that case, it is nevertheless necessary to ensure that the gained experience is underpinned by further experiments. In addition, it must be classified in higher theoretical frame of reference of engineering education research. The presented work may act as a hotbed for further evidence-based research in this direction.

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8 Appendix A

The items used for the laboratory competence development questionnaire refer to the learning outcomes developed by Feisel and Rosa (2005). In the following, the numbers used in Figures 6 and 7 are assigned to the respective items:

- Handling laboratory equipment, measurement tools and software for experimentation
- Identifying strengths and weaknesses of engineering specific theoretical models as a predicator for real material behavior.
- Planning and executing common engineering experiments.
- Converting raw data from experimentation to a technical meaningful form.
- Applying appropriate methods of analysis to raw data.
- Designing technical components or systems on Basis of experiments results.
- Recognizing whether or not experiment results or conclusions based on them "make sense".
- Improving experimentation processes on basis of experiment results, that do not "make sense".
- Relating laboratory work to the bigger picture and recognizing the applicability of scientific principles to specific real-world problems in order to solve them creatively.
- Choosing, operating and modifying engineering equipment.
- Handling technological risks and engineering practices in responsible way.
- Presenting experimentation results to technical and non-technical audiences in written form.
- Presentingexperimentationresultstotechnicalandnon-technicalaudiencesinoralform.
- Working effectively in a team.
- Applying professional ethical standards in terms of objectivity and honesty in context with data handling.

9 Appendix B

The items used for the technical perspective (items 1-5) and the course perspective (items 6-15) are shown below. Items 16-20 include an overall assessment of the laboratory environment and its evaluation for the teaching-learning process. In the following, the numbers used in Figure 8 are assigned to the respective items:

- The laboratory system (online platform and experiment equipment) was easy to use
- The laboratory system worked without any technical problems
- The response time of the laboratory system was adequate
- The streamed video was of high quality
- Theusedonlineplatformfortheexperimentationitselfisofhighqualityandwelldesigned
- The objectives of the experiment were clear to me

- I was able to fully use the laboratory system by following the instructions in the tutorial video
- I would prefer some further help by any tutor in carrying out the experimentation
- I understand the connection between the experiment and the given case for the results' practical application
- I was able to acquire all relevant data from the experiment
- The next step was clear to me in every moment of the experiment and I knew what to do as well as how to do this
- The assigned time slot gave me enough time to fully carry out the experiment
- The video streaming of the live experiment was helpful for me
- I understand how the equipment components (robot, testing machine, measurement technology, camera) being used for the experiment work and how they are connected
- The experimentation process could be carried out in groups by using Adobe Connect and I could share what I was doing with others
- Performing the experiment helped me better understand the related theoretical concepts (stress strain diagram, yield strength, etc)
- Performing the experiment enhanced my ability to apply theoretical concepts learned in lecture
- This online experiment was a useful learning experience for me
- Such remote laboratory systems are an adequate opportunity to connect students all over the world and letting them carry out experiments
- I wish that online experiments like these could be extended to other cases, contexts or subjects