Development of WebXR-based Environment for Engineering Experiments

Yuji Teshima
Control Engineering Dept.,
National Institute of Technology
Sasebo College
Sasebo City, Nagasaki, Japan
teshima@sasebo.ac.jp

Akihiro Sakaguchi
Control Engineering Dept.,
National Institute of Technology
Sasebo College
Sasebo City, Nagasaki, Japan
sakaguch@sasebo.ac.jp

Yuto Mitsue
Control Engineering Dept.,
National Institute of Technology
Sasebo College
Sasebo City, Nagasaki, Japan
s1734@st.sasebo.ac.jp

Nobutomo Uehara
National Institute of Technology,
KOSEN Japan
Hachioji-City, Tokyo, Japan
uehara@kosen-k.go.jp

Kazuhide Sugimoto
National Institute of Technology,
KOSEN Japan
Hachioji-City, Tokyo, Japan
k_sugimoto@kosen-k.go.jp

***Abstract*—This study presents an improved online/on-demand educational approach to engineering experiments by introducing an interactive 3D virtualized environment. This study aims to verify the possibility of the morphological evolution of fully online/on-demand engineering experiments by enabling the interactive operation of equipment and devices in a 3D virtual space. For this purpose, we developed an extended reality-based engineering experiment system that students can use through a web browser online/on-demand to conduct engineering experiments in a virtual space without requiring actual experimental equipment. By comparing the assessment results of the virtual experiments with on-campus real operation of equipment in the previous year, the educational effectiveness of introducing a virtualized environment that enables interactive online operation of 3D-modeled equipment on a web browser has been confirmed.**

Keywords—WebXR, virtual reality, engineering experiments, online education

I. INTRODUCTION

Engineering experiments are crucial components of the engineering curriculum in higher education, they enhance students' knowledge and engineering skills. However, students have different understandings of the theoretical principles and background. The diversity of learning speeds, comprehension depths, and technical skill acquisition through engineering experiments has recently increased among students. Therefore, the development of adaptive learning environments and related educational content is urgently required. A transition to a tailor-made education is strongly expected to solve this issue and should be used in engineering experiments [1]. In addition to developing adaptive learning environments [2-4] and related educational content, establishing an online/on-demand approach plays a significant role. However, there is little collaboration between engineering experiments and educational systems using information and communication technology (ICT) [5]. The coronavirus pandemic has also necessitated online educational approaches to engineering experiments [6]. Therefore, we tried to implement a fully online educational approach to engineering experiments last year by carefully selecting experimental items that were expected to have the same educational effect as on-campus steering. One was superposition theorem to the second-grade students and the other was servo-motor speed control to the fifth-grade students in the control engineering department [1]. The effectiveness of this approach was confirmed through the results of the ex-post questionnaire and assessment of experimental reports. However, some issues were noted in the fully online approach, such as the necessity of collaboration in environment construction and communication tools installation and a lack of accomplishment caused by the difficulty in operating the devices and equipment. As for the latter, virtualized environment construction is expected to enable interactive operations of equipment. Recently, there have been many reports on the introduction of virtual reality (VR) and mixed reality (MR) technology into education [7-13]. Therefore, we developed an extended reality (XR)-based engineering experiment system that students can use through a web browser online/on-demand to conduct engineering experiments in virtual space without requiring actual experimental equipment. Thus, this paper reports the results and effectiveness of using an XR-based approach.

II. XR-BASED SYSTEM FOR ENGINEERING EXPERIMENTS

"XR" is a general term for advanced technologies such as VR, augmented reality (AR), and MR. In this paper, XR denotes VR, a technology that builds an environment in virtual space that is essentially equivalent to reality.

A. Problems with using an XR-based system

Educational and training systems based on XR technology have also been proposed and developed in education [14-16]. However, many systems require special equipment, such as head-mounted displays (HMDs), haptic devices, and motion sensors. In these cases, we have to pay attention to the problem of VR sickness, which is caused by the inconsistency between the original human senses and the senses in virtual space [17]. Therefore, we developed an XR-based engineering experiment system considering the following points.

- No HMD installation is necessary
- Works on a web browser

B. Targeted engineering experiment theme

We selected the "resistance measurement by Wheatstone bridge" engineering experiment for second-grade students in the control engineering department. In this experiment, the error is evaluated from the measured values of the target resistance and induction coil by operating the experimental equipment and measuring the resistance. Until the previous year, this experiment was performed in the laboratory by sharing equipment, as shown in Fig.1, with 4 or 5 members in each group.

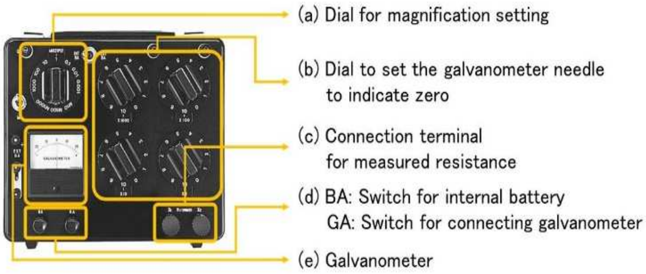


Fig. 1. Portable Wheatstone bridge

C. Construction of an XR-based engineering experiment system

To develop an online/on-demand engineering experiment based on virtualized equipment operation, a portable Wheatstone bridge (YOKOGAWA IM2755) was selected, and its 3D model was created. The Blender software was used for modeling. Further, a server for the XR-based engineering experiment system was constructed to realize the operation of this experimental system from a web browser. This experimental system was developed using MRToolKit under the Unity environment, as shown in Fig.2. Here, the programming language #C was used for development.

III. XR-BASED ENGINEERING EXPERIMENTS

A fully online approach was developed by selecting the experimental item Wheatstone bridge; this approach was expected to have the same educational effect as on-campus experiment performance. In the online approach, Google Classroom was selected as the learning management system (LMS), and on-demand teaching materials were prepared such that students could proceed with the experiment at their pace. In addition, an explanatory video on the basic principles, use of the measuring equipment, experimental method, data processing, point of consideration, and documents required for on-campus experimentation were prepared. Students could download these materials, which can be referred to repeatedly. Fig.3 shows the top menu of a class for the experimental item Wheatstone bridge on Google Classroom. A laptop was provided to all students. Instead of the actual equipment, each student proceeded with the measurement using an XR-based engineering experiment system according to the experimental procedure manual with related contents provided on the LMS.

A. Measurement procedure

Using a virtual environment that simulates a portable Wheatstone bridge, fixed resistance and induction coil resistance were measured by each student.

1) Procedure for fixed resistance measurement

- Connect the resistance to be measured to the terminal. (See Fig.1 (c))

(a) Top view (b) Bird's eye view

Fig. 2. An extended reality-based engineering experiment system.

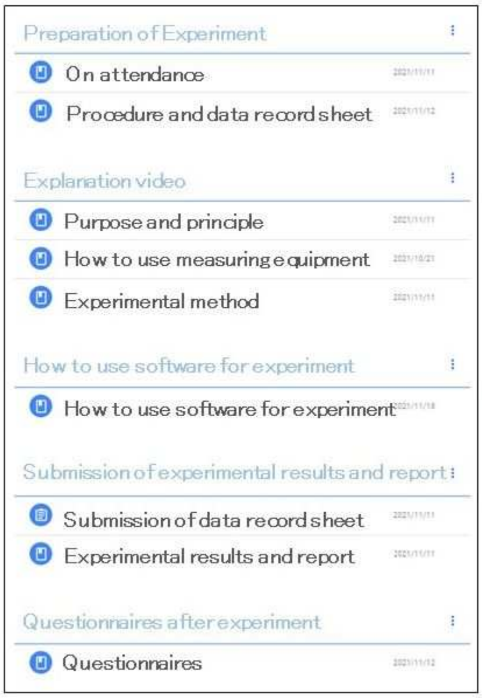


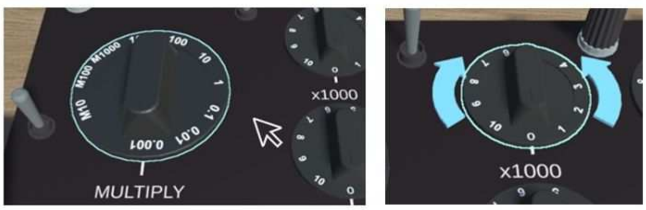
Fig. 3. Top menu of a class for the experimental item Wheatstone bridge.

- Set the MULTIPLY dial according to the resistance value to be measured. (See Fig.1 (a))
- Push the BA button, then press the GA button for a moment. (See Fig.1 (d))
- Rotate each dial to set the galvanometer needle to indicate zero. (See Fig.1 (b))
- Reset both BA and GA buttons off at the end of the measurement

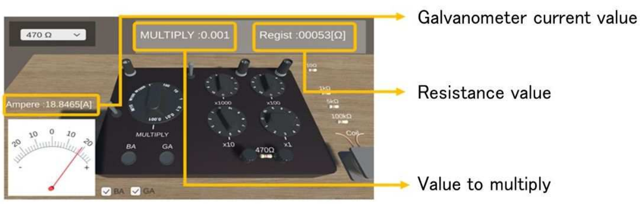
2) Procedure for inductive coil resistance measurement

- Connect the inductive coil to be measured to the terminal. (See Fig.1 (c))
- Equilibrate the galvanometer needle to zero as in the fixed resistance measurement.

Fig,4 shows the user interface and dial operation example of the XR-based experimental equipment system (the XR-based system).



(a) Dial operation example



(b) User interface

Fig. 4. Experimental equipment user interface and dial operation example

Fig. 5. An operation example of the extended reality-based experiment system.

B. User operation of the XR-based system

- Selection and connection of the measurement target can be operated using the mouse.
- Dial operation can also be performed using the mouse.

Fig.5 shows a student operating the XR-based system.

IV. COMPARISON OF RESULTS

To confirm the effectiveness of the online/on-demand approach to engineering experiments, the results were assessed by the same faculty member who was on campus the previous year. The preparation status, activities, and quality of the final report were unchanged from the on-campus assessments. In addition, the students self-assessed the online approach and its effectiveness in a questionnaire. Questions had only two choices, "yes" or "no," to eliminate ambiguous answers. All items in the questionnaire were provided with spaces for free-form comments by students.

A. Comparison of assessment results

Table I compares the means and standard deviations (SDs) of the assessment scores of the experimental reports. All reports were marked out of 30. The assessment scores of the XR-based experiment were compared with those of on-campus reports submitted in the previous year.

1) *Mean values of assessment scores of experimental reports and overall scores have better results than the previous year.*
2) *SDs of assessment scores of experimental reports and overall scores have markedly lower scores compared with the previous year.*

The assessment scores were improved by introducing the XR-based engineering experiment system in 2021. In addition, because SDs of the assessment scores decreased, it can be said that the variation in the comprehension levels among students also decreased.

TABLE I. COMPARISON OF ASSESSMENT RESULTS

Report / Overall	**2020**		**2021**	
	Mean	**SD**	**Mean**	**SD**
Report (30)	21.6	4.7	24.1	3.9
Overall (100)	86.9	8.1	93.4	4.9

B. Questionnaire items and response results

The questionnaire administered to students included the following items: (parentheses enclose the percentage of positive response results to each questionnaire item in 2021)

Q1) After watching the explanatory videos, did you understand the principles and characteristics of the experiment? (97.3%)

Q2) After watching the explanatory videos, did you understand how to handle and connect the measuring equipment? (100.0%)

Q3) After watching the explanatory videos, did you understand the experimental contents and measurement method? (100.0%)

Q4) Using the XR-based engineering system, did you obtain and record the measured data? (100.0%)

Q5) Did you process the acquired data based on the explanation videos? (97.3%)

Q6) Did the environment where you can watch videos and materials explaining the experiment at any time help you understand its purpose and procedure? (100.0%)

Q7) Did the environment in which you can watch explanatory videos and materials at any time help you understand the data processing? (100.0%)

Q8) Do you think that the environment in which you can watch videos, measure data through the XR-based system and analyze data at your own speed can deepen your understanding of the principles and characteristics of the experiment? (83.8%)

Q9) Did you feel a "sense of accomplishment of learning" through the XR-based system in which data can be measured and organized at your own speed? (94.6%)

Q10) Were you able to reduce the preparation time in the total experimental time by watching the video explaining the experiment preparation part and browsing the related materials for the use of the XR-based system in advance, and did you use the time thus created for measured data analysis and report writing? Do you think that the online approach improved the efficiency of the experiment? (94.6%)

Q11) What are your thoughts on the online/on-demand approach to the engineering experiment, mainly based on an XR-based system? Does it seem to be the right way forward? (97.3%)

Q12) Do you think that the environment in which you can measure data through the XR-based system and analyze data at your own speed can deepen your understanding of the principles and characteristics of the experiment? (100.0%)

The following points are derived from the response results in 2021.

1) *Effectiveness of the on-demand approach*
   From the questionnaire responses to Q1)-Q3), Q5)-Q8), Q10) from students, many positive answers to the on-demand approach were ontained. It is because that the online contents are able to watch repeatedly at any time at their own pace.

2) *Possibility of XR-based engineering experiment*
   From the questionnaire responses to Q4), Q8), Q11)-Q12), XR-based approach seems to be effective and welcomed by students.
3) *Sense of accomplishment in learning*
   From the questionnaire responses to Q9), a sense of accomplishment in learning seemed to be apparently gained by students. It can be said that XR-based approach enables to bring the same learning experience as using the real equipment.

Table II compares the questionnaire response results between in 2020 and in 2021. Because the XR-based system was not introduced in 2020, response results were obtained to the following different questionnaires from item Q9) to Q11) in 2020.

Q9) Do you think that the environment in which you can watch videos, measure data through the measurement video and analyze data at your own speed can deepen your understanding of the principles and characteristics of the experiment? (57.9%)

Q10) Did you feel a "sense of accomplishment of learning" through the online/on-demand engineering experiment in which data can be measured and analyzed at your own speed through both the explanatory and measurement videos? (76.3%)

Q11) The measurement data of the experiment could be submitted online at any time until the submission deadline, and you will receive a quick response to your submission from the faculty members. Do you think that such an online/on-demand approach to engineering experiments helps you improve your experiment report's quality? (78.9%)

To check for significant differences between the responses before and after introducing the XR-based system, a Welch t-test (significance level = 0.05, two-sided test) based on the differences in mean values was applied. Each "yes" and "no" answer was scored as 1 and 0, respectively. The sample size of the group in 2020 was 42 and the one in 2021 was 37, respectively. The differences between the two groups of students were significant for items 9 ($p = 0.001$), 10 ($p = 0.025$), and 11 ($p = 0.014$). After introducing the XR-based system in 2021, scores exceeded those in the previous year.

C. *Free-form comments from students*

Before introducing the XR-based approach, the following comment was received from students.

- Real experience in the laboratory makes it easier to understand the actual procedure of the experiment by handle the devices and equipment physically.

From the free-form comments by students in 2021, the XR-based approach for engineering experiments seems to be acceptable and welcomed by students. Typical reasons for the students' answers, extracted from the free-form comments, are as follows.

TABLE II. COMPARISON OF THE QUESTIONNAIRE RESPONSE RESULTS FROM ITEM Q9) TO Q11) BETWEEN IN 2020 AND 2021

Year	***Q9)***	***Q10)***	***Q11)***
2020	57.9%	76.3%	78.9%
2021	94.6%	94.6%	97.3%

- The XR-based system was a realistic one
- With the experiment feeling real, it seemed like we were actually operating the equipment
- It was almost the same as a real experience in the laboratory, and made it easier to understand the actual procedure of the experiment
- A sense of accomplishment in learning was received, because all of the work has to be done by oneself
- Having to do much work by oneself leads to a deeper understanding

The last two comments are interesting and impressive. In on-campus experiments, the item Wheatstone bridge was shared by four or five students in a group. By introducing the XR-based system, each student could handle their equipment. While positive comments were obtained as described above, some negative comments were also obtained.

- Some students reported discomfort because they did not physically handle the devices and equipment.

V. CONCLUSION AND FUTURE WORK

This paper reported the development of an XR-based system for online/on-demand engineering experiments. Its educational effectiveness in introducing a virtualized environment that enables interactive online operation of 3D equipment model using a web browser has been confirmed. The assessment scores were improved by introducing the XR-based engineering experiment system. In addition, the variation in the comprehension levels among students also decreased. Through students' responses to an ex-post questionnaire, the introduction effectiveness of the virtualized approach was also confirmed by a sense of accomplishment. Many positive, free-form comments were received from students, saying that they seemed to be actually operating the device and equipment with a realistic model. In addition, the WebXR approach enables each student to handle the expensive equipment, which is commonly shared and used among group members. Furthermore, having to do a lot of work by oneself at one's own pace leads to a deeper understanding. From the viewpoint of a tailor-made education experience, the virtualized environment seems effective in expanding online/on-demand possibilities of experimental items that require the operation of equipment and devices in the laboratory. In further study, we will introduce the following measures and verify their effectiveness.

- Collaborative work among group members in a metaverse environment
- Introduction of online communication tools using avatars
- Real-time analysis of online experiment logs for accurate advice from faculty members

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