An Integrated Framework to Support Bachelor Design Students in 3-D Modeling

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Abstract—Design and computer graphics curricula for tertiary education include 3-D modeling skills. Students have to learn to represent (complex) 3-D objects by means of parametric surfaces or polygonal meshes. Three-dimensional modeling may be a complex task and students have to be able to accrue a certain deal of experience in the field before passing the exam. The main difficulties the students have to face mainly concern the comprehension of 3-D shapes and the choice of the most appropriate modeling techniques. This paper proposes a framework to support bachelor students of the design degree in modeling 3-D objects by means of parametric surfaces. The proposed framework provides two augmented reality (AR) apps for smartphones and a web portal. The mobile AR apps allow students to deeply visualize 3-D object shapes, thus performing a set of guided exercises in order to take practice in basic modeling techniques. On the other hand, the web portal allows students to share their models with teachers and classmates to get feedback and comments. Preliminary results show the effectiveness of the proposed solution as all volunteers involved in the experimental phase achieved better results after using the tools. Moreover, the students' opinions about the proposed framework are positive.

Index Terms—Augmented reality, object modeling, homework support systems, self-assessment, online assessment tools.

I. INTRODUCTION

COMPUTER graphics and design curricula include 3-D modeling skills. Modeling is a complex task and several different strategies are used to support students in their learning activities. This area of expertise is absolutely strategic for the design field, while being instrumental to wide variety of purposes: early concepts development, morphology of the objects, visualization, ergonomics, prototyping, 3-D printing, testing production, and customization are just some relevant ones. Design relies on 3-D modeling techniques so that they must be adopted by all the students like any other design-related skill [1].

Authors of this paper have been teaching 3-D modeling for about two decades; in particular, they are currently involved in teaching the "Digital models and geometry" course of the bachelor program in Design and Communication. Students of this class have to face a lot of challenges and only $60\% - 80\%$ of them is able to pass the exam in the same academic year as the enrollment.

During the exam of "Digital models and geometry" students are required to model a 3-D object starting from a set of images representing the object itself framed from different points of view (students usually can choose from three or four different objects). Images can be used as background to draw parametric curves and profiles, thus obtaining surfaces by operations such as: revolve, rail revolve, loft, curve network, and so on. Different surface patches are then merged/blended together to obtain the final object shape.

At the end of the course, the University asks students to fill a questionnaire about the teaching quality of each class; a part of the form can be used to outline the problems encountered in the learning experience. Issues related to the preparation of the exam have been gathered for several consecutive years; the following items represent the main problems:

- it is difficult to understand the 3-D shape of an object;
- it is not possible to get an assessment for exercises performed during the self-study;
- it is difficult to identify the right operator (modeling technique) in order to obtain the desired outcome;
- it is difficult to approach 3-D modeling when unsupervised;

Indeed, the first issue is common when students approach the 3-D modeling for the first time. Students need a lot of practice to understand 3-D shapes and some people struggle more than others to acquire this skill. Moreover, although all 3-D modelers provide a perspective viewport, the modeling process is intrinsically 2D as the designers basically draws curves and other primitives in orthographic viewports (top, right, front, bottom, left, and back). The second issue is a general problem: how can students get a feedback about exercises they perform autonomously? Although some exercises can be developed by the teacher during the lessons, it is not possible to provide students an assessment for any homework and this can prevent students to get a feedback about personal preparation. The third issue is well known to 3-D modeling teachers: in general, there is not a unique solution to make a 3-D shape, more approaches can be almost equivalent and just a lot of practice can help students to identify the most suitable solution. On the other hand, some kind of support should be necessary at the beginning of the teaching process for facilitating students to learn the right methodology also during the self-study. The last issue is strictly connected to the third one: the lack of experience can be offset only by a continuous support of the teachers.

Even though design students learn to model by parametric curves and surfaces using the Rhinoceros software [2], the above mentioned problems are more general and can affect also other modeling techniques (e.g., solid and polygonal modeling). The above analysis outlines how the self-study is a critical moment and standard material (textbooks, slides and tutorials) might be not sufficient to profitably support students in their learning path.

This paper presents an integrated framework to support students during their self-study activities; the proposed approach might be easily extended to any kind of 3-D modeling technique. First of all, a mobile augmented reality (AR) viewer app allows students to deeply explore 3-D shapes of objects to be modeled; in this way, the gap between 2D viewports and 3-D model can be overcome. Secondly, a set of guided exercises related to basic Rhinoceros' operators allows students to fix the methodological approach to 3-D modeling, thus assessing the theoretical personal preparation; these exercises are also based on mobile AR. AR technologies proved to be effective in improving learning experience in preschool, grade school and high school education [3], [4] and [5]. In particular Billinghurst and Duenser in [3] explained that AR can:

1) illustrate spatial and temporal concepts;
2) emphasize contextual relationships between real and virtual objects;
3) provide intuitive interaction;
4) visualize and interact in 3-D;
5) facilitate collaboration.

These abilities of AR might help students in improving their 3-D modeling skills. User can get highest benefits from wearable AR devices (such as the Microsoft Hololens); on the other hand, also handheld devices, which implement the mobile AR paradigm, can help students both to improve 3-D visualization and to understand relationships between real and virtual objects [6].

As benefits of online self-assessment tools are well known in the literature (e.g., [7]), the third part of the framework is a web portal that offers students the opportunity to upload models, thus receiving an automatic evaluation; moreover, comments can be exchanged between the teacher and students for each model, thus providing a continuous support. Twelve students have been involved in a preliminary experimental phase and results, requiring further validation, show that students achieved better results after using the tools.

The rest of the manuscript is organized as follows: Section II reviews the use of AR, self-assessment systems and feedback strategies to support learning paths, whereas Section III presents the proposed framework. Section IV describes the experimental phase and discusses the obtained results.

II. RELATED WORK

This section reviews: the use of AR in education, self-assessment solutions to support students during individual study and types of feedback. Although 3-D modeling was previously considered to integrate makerspaces and maker-centered learning experiences of heterogeneous undergraduate and graduate college students [8], to the authors' best knowledge there is no solution in the literature that concurrently considers and evaluates self-assessment, AR and feedback strategies to support undergraduate design students of 3-D modeling classes.

A. AR in Education

AR has found its initial application in six domains: medicine, manufacturing and repair, annotation and visualization, robot path planning, military applications, and entertainment [9]. Other important areas followed such as tourism, architecture, cultural heritage, and education.

Several teaching activities can take advantage from AR and a lot of work has been published to outline the impact of AR technologies on different fields such as: Medicine [10], [11], Engineering [12], [13], Architecture [14], [15], Chemistry [16], [17], Mathematics and Geometry [18], [19], Physics [20], [21], Geography [22], [23], Astronomy [24], [25], History [26], [27], Archaeology [28], [29], Music and Art [30], [31], and many more. AR has been also used to support computer graphics teaching [32] and [33]: results showed a high pass rate as well as increased engagement and student satisfaction. Moreover, educational issues related to the use of AR have been also investigated; for instance, Abdinejad *et al.* [34] gather students' feedback on the effectiveness and perception of molecular visualization tools based on AR. The students' experience is analyzed to obtain feasibility insights on how AR could support the teaching-learning process in math [35], whereas [36] explores the effect of AR on students' self-efficacy and conceptions of learning physics.

AR might allow students to study in a more exciting way and educators/teachers/trainers can design ad-hoc learning paths, which exploit AR abilities to improve students' learning experiences [37]. The educational effectiveness of AR depends on several different factors [38]; results (in terms of students' performance) can be strongly different with respect to a "traditional" approach or they can be almost the same. Indeed, the design strategy of the AR-based learning experience deeply affects the final impact on students and three main issues should be mainly considered:

1) enabling the exploration of AR content and encouraging further study;
2) promoting the collaboration and encouraging students to exchange ideas;
3) ensuring that AR content are engaging (more than traditional study supports).

The impact of each solution can be also measured (e.g., [37]), thus assessing the effectiveness of any AR application for education. Although there are several AR solutions to support students in learning and understanding 3-D spaces (e.g., [39], [40] and [41]) applications fully targeted to support 3-D modeling are missing. In this paper, two AR apps are proposed (see Section III-B2): the first one (ARViewer) belongs to the category of apps devoted to enhance the comprehension of 3-D shapes/geometries; on the other hand, the app ARPractice enables students to apply modeling techniques by a stimulating and engaging way.

B. Online Self-Assessment

Contemporary design principles and methods are based on a systemic view, not only targeted to design products but also to support connections among designers as suggested by Jones [42]. This networking approach uses different tools to achieve design goals within multidisciplinary teams and the self-assessment is one of them, enhancing the engagement perception of people involved in the design processes, even if they are not designers. A practical example is the Open Design culture, defined by its communities of designers, where projects are shared and evaluated by anybody inside, or even outside the design team [43]. This scenario offers an optimal environment for the use of self-assessment strategies and tools, while education is in first line to make this processes part of future designers toolbox [44]. Self-assessment solutions can also result in benefits both for teachers and students [45]; in particular, self-assessment is more oriented to students and it may reduce the teachers' workload, provides immediate feedback and can help to remove certain communication obstacles between teachers and students.

There are several works that consider online assessment in higher education. For instance, Gikandi *et al.* [46] present a literature review of 18 studies. The impact of formative assessment is analyzed both for blended and online teaching. The results of this survey outline that an effective online assessment can help to align teaching and learning; moreover, a formative assessment is a possible way to bridge the gap between knowledge and know-how. Wilson *et al.* [47] analyze the effectiveness of computer-assisted assessments and the relationship with exam performance (the same approach is also performed in this work, see Section IV). The exam results showed that students involved in the experiment achieved over 10 better results than the others. Subjective feedback are also gathered in De Marcos *et al.* [48]; results pointed out the benefits in terms of user satisfaction and better performance. Finally, a correlation between the effects of self-assessment tests on the population of students over several years and control variables such as other courses in the same year has been also performed in [49].

Strategies for automatic assessment of OpenGL graphics programming for 3-D modeling can be found in [50] and [51]; in these cases, automatic tools use invariants and intermediate data obtained from the OpenGL state machine and rendering pipeline to compare a proposed solution and a reference code. Related works more specifically concerning online/self-assessment of 3-D modeling by CAD software can be found in [52], [53] and more recently [54]. All these works outlined how self-assessment tools can result in benefits both for students and teachers.

C. Feedback

Feedback can deeply impact on students learning. This impact can be either positive or negative and different types of feedback can be differentially effective [55]. The model proposed by Hattie and Timperley defines that an effective feedback should answer three different questions: "where am I going?", "where am I now?" and "how can I close the gap?". Three different types of feedback can be used to effectively answer these questions: task-level feedback, process-level feedback and self-regulation feedback. The first type of feedback (task-level) is focused on information (correct or incorrect) and it basically provides students information about how well a task has been performed. Process-level includes feedback specific to the processes underlying the tasks or relating and extending tasks. Feedback at this process-level appears to be more effective than at the task-level for enhancing deeper learning. On the other hand, self-regulation feedback focuses on students that are able to monitor their own learning processes; this level should enhance self-evaluation.

The impact of feedback has been deeply investigated; for instance, formative feedback is provided to support complex problem solving in a required first-year course in engineering design and practice [56]. Automatic assessment and formative feedback generation for OpenGL modeling assignments is presented in [57]; in this case, feedback is expected helping students when coding errors occur rather than providing a methodological feedback. Also the impact of feedback from peers has been investigated in the literature (e.g., [58]).

The proposed framework proposes all three feedback types: the app ARPractice is more focused on task-level feedback, the web portal provides students self-regulation feedback and the instructor's comments are mainly focused on the 3-D modeling process methodology.

III. THE PROPOSED ARPROJECT FRAMEWORK

The purpose of this research is to support students attending for the first time a 3-D modeling course. To this end, a novel framework has been designed, developed and tested on a classroom of students attending the "Digital models and geometry" course of the Bachelor Degree in Design and Communication at the Politecnico di Torino. The following sections describe all the design steps.

A. Requirements and Scenarios

The first step of the design process has been to collect user requirements from both the students and the teachers point of view. Students have to attend this course in the first year and 3 academic credits are recognized; a credit is equivalent to 10 hours of lesson and 15 hours of self-study. Students are required to model objects by means of parametric curves and surfaces using the Rhinoceros software. A learning by doing approach is adopted: lessons are taught in laboratory and students can immediately apply theoretical concepts through targeted exercises. The "Digital models and geometry" class is propaedeutical to other teaching activities related to computer graphics such as rendering and animation. Moreover, the course is taught in parallel to other two modules of the "Representation project" atelier: "Descriptive geometry and digital representation" and "Graphics tools and digital media". This can be a brake on the course of study as the 12 academic credits of the "Representation project" atelier can be recognized only when the exams of all the three classes have been passed.

This class usually consists of about 80 students and the main challenge is that students have to focus on multiple information channels while attending a lesson:

- the teacher;
- lesson slides, which resume the key concepts described by the teacher;
- a computer, which each student uses in a learning-by-doing approach;
- a notebook, used by the students to write down key concepts, notes, and valuable hints.

However, when the students review the lessons at home, during their self-study, they may encounter multiple difficulties, such as:

- concepts may be unclear;
- there is no one to ask for a clarification till the next lesson;
- missing clues to complete an exercise;
- missing feedback respect to the approach carried out to complete an exercise.

All these challenges tend to baffle and to strain the students, whose motivation may quickly decline, leading them to disregard homework. Thus, it is necessary to design a set of "tools" able to support and motivate students. At the end of the class, the students' deficiencies are due to lack of practice (post-teaching surveys and tutors' feedback outline this issue) that is fundamental to effectively approach the 3-D modeling. The proposed framework has been designed to address these issues: by an intriguing and innovative technology such as AR, students should be enticed to approach 3-D modeling in a different way with respect traditional lessons/tutorials, thus encouraging them to spend more time to practice; moreover, the web portal should bridge the gap between students and teacher during self-study. Since the research goal and the domain have been defined, the next step consists of identifying possible scenarios.

Students have to practice through homework for the next lesson; basically, one or two objects have to be modeled by the techniques taught by the teacher. A student has to perform the following steps:

1) understanding the assignment; the student gets support by slide and personal notes or he/she looks for online tutorials;
2) carrying out the assignment; this could lead to three possible outcomes:
   - the student is able to correctly complete the assignment;
   - the student is unable to complete the assignment;
   - the student completes the assignment but he/she makes one or more mistakes.

Students unable to complete the assignment could be discouraged, but a wrong self-assessment can affect the emotional status of students: security, doubt or annoyance, due to the lack of feedback can lead to a poor personal preparation, thus increasing the possibility to fail the exam.

B. The Framework Architecture

The requirements analysis and the definition of possible scenarios contributed to define the functionalities required by
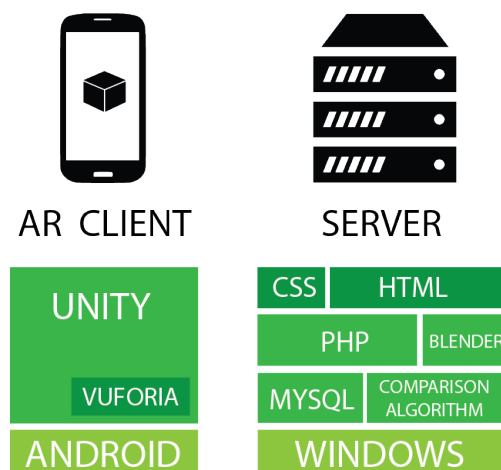

Fig. 1. The software layers adopted for developing the server and the client apps.

the proposed framework. The goal is to obtain a system that allows students to practice at home, receiving guidance and feedback in a intriguing and stimulating way. Therefore, the framework should:

- provide guidance for 3-D modeling exercises and assessing the learning level of theoretical and methodological concepts necessary to properly complete the assignments;
- provide a grade for each exercise carried out by the students;
- allow the teacher to provide feedback to the students.
- allow students to collaborate each other to solve problems.

The students should practice 3-D modeling through their PCs at home. Two distinct mobile applications have been developed to guide the students through the modeling process. When the students complete their exercises, they can upload their model through a web portal, which provides both scoring for the assignment and the chance to interact with the teacher (and the other students) by providing comments to the uploaded models, in order to get clarifications for each exercise. Fig. 1 shows the software layers adopted for developing the proposed system.

1) The web portal: The web portal provides different functionalities for students and teachers. Firstly, there are two categories of contents: public and login-based. The homepage displays a list of (public) objects modeled by students, as shown in Fig. 2. Clicking on the model preview, a new page is opened, which displays: a preview of the model, a description provided by the student and a button to download the object in OBJ format.

The top bar menu allows users to browse:

- the references page, which shows the list of all the available references uploaded by the teacher. Visiting the page of a single reference allows the students to: view a preview of the 3-D model, read the description provided by the teacher (which can include tips or suggestion for modeling the given object) and download the reference and a set of images representing different views of the
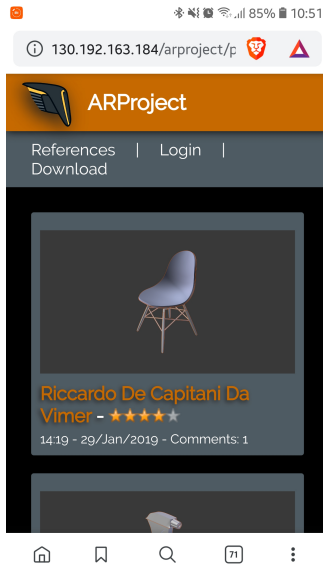
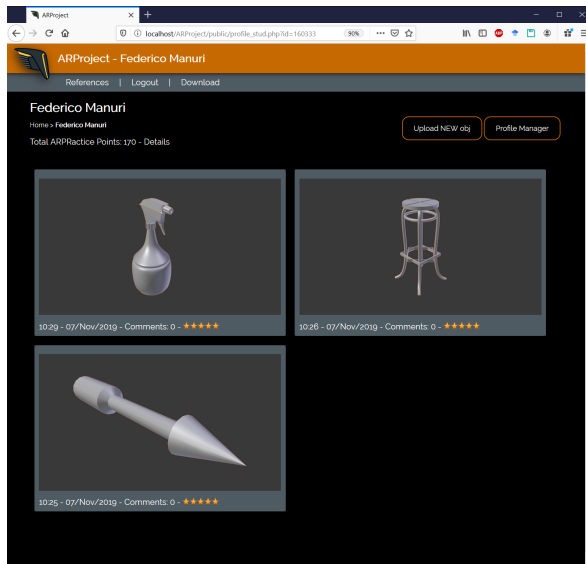Fig. 2. A mobile view of the web portal home page.

Fig. 3. The student's personal page.

object (these images are the same kind of information students receive as exam outlines);
- the login page, in order to access to the non-public content;
- the download page where the AR apps and the image (target) used by the tracking system are available for downloading.

The users have to log in to access the utilities provided by the web portal, thus the system can differentiate between students and teachers depending on the access credentials. Once logged, students are redirected to their personal pages (Fig. 3), which display:
- the total points earned through the exercises of the ARPractice app: the "Details" link opens a new page presenting the list of exercises performed and the total points earned for each one;

- a list of models uploaded by the student (if any) with the time/date information of the upload, the number of comments for that model and a rating;
- a "Upload NEW obj" button, which opens a new page for uploading an object modeled by the student: the procedure requires to select a file from the computer browser, indicate the corresponding reference name from a radio button list and eventually provide a description of the uploaded model (e.g., problems encountered while modeling the object); after completing the upload, the server performs a comparison between the model provided by the student and the selected reference object. The comparison is performed through a Blender [59] script based on the algorithm presented in [60] (the algorithm is able to consider affine transformations) and also used in [53]; depending on the value provided by the script, denoting the dissimilarity DI of the two objects (uploaded and reference), the server assigns a score to the student's model, represented by "stars" (up to a maximum of five stars when the object uploaded by the student is almost indistinguishable from the reference one). The number of stars NS were experimentally found and it can be expressed as:

$$NS = \begin{cases} 0 & \text{if } DI > 5500 \\ 1 & \text{if } 4500 < DI <= 5500 \\ 2 & \text{if } 3500 < DI <= 4500 \\ 3 & \text{if } 2500 < DI <= 3500 \\ 4 & \text{if } 1500 < DI <= 2500 \\ 5 & \text{if } DI <= 1500 \end{cases} \quad (1)$$

The gamification mechanism of reward is introduced here and in the ARPractice app (see Section III-B2) to encourage students to keep practicing. The effect of virtual achievements on student engagement has been investigated in [61];
- a profile manager button, which allows users to change their password.

On the other hand, the teacher can see all the uploaded models, thus providing comments about the students' works. The personal page of a student is loaded when the teacher clicks on the student's name. In the top bar menu, the system manager option leads to the control page of the whole framework (Fig. 4). From this page, the teacher can access:
- the references' manager page, which allows the teacher to add new references or edit and/or delete the existing ones;
- the uploads' manager page, which provides a list of all the models uploaded by the students, displaying for each one: a preview of the 3-D model, the student's name and the reference model, the upload date, the score computed by the similarity script, and the corresponding rating;
- the categories' manager page, which lists all the available categories and allows the teacher to add new categories or edit and/or delete the existing ones;
- the exercises' manager page, which lists all the available exercises for the ARPractice app; the name and number of
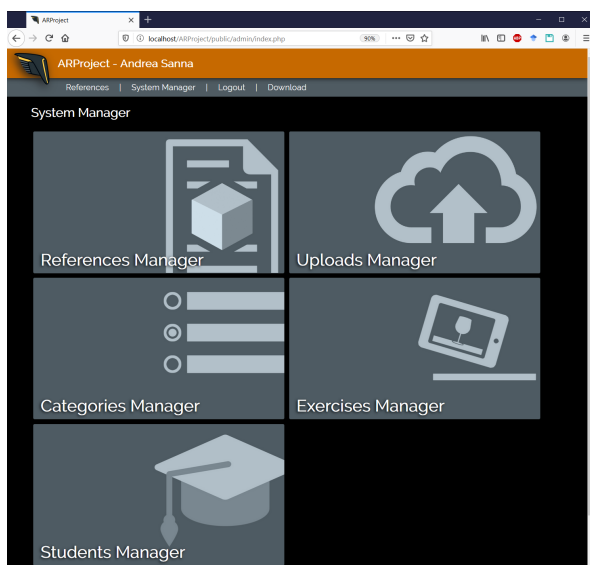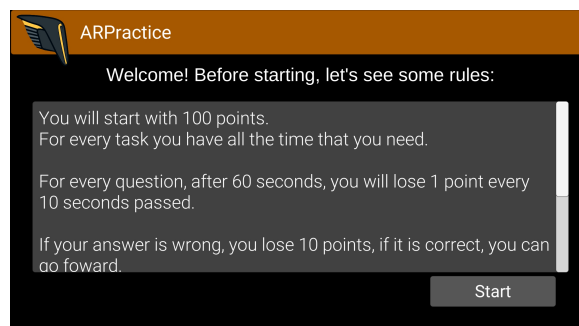
Fig. 4. The control page of the web portal.

Fig. 5. Instructions for the ARPractice exercise.

Fig. 6. Once the reference image has been framed by the camera, the current question and a set of possible answers are displayed to the student.
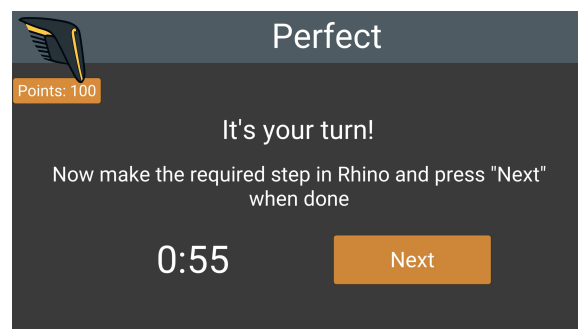

Fig. 7. The student is asked to perform the given step by Rhinoceros.

questions for each exercise is provided. This page allows the teacher to delete and edit existing exercises or to create new tests (see the next section for more details);

- the students' manager page, which both provides information of all the students' accounts and enables to add new students or edit and/or delete the existing ones.

2) Augmented reality applications: The mobile applications have been developed in Unity and, since they are AR based, the Vuforia SDK has been adopted to perform the tracking (Fig. 1).

The ARPractice app guides the students step by step in the process of modeling a 3-D object, starting from the theoretical and methodological concepts and moving on to actually perform the modeling in Rhinoceros. Once the student has chosen an object to model, he/she can start the ARPractice app. After the login, the app displays the student full name and the sum of the points earned for each completed exercise. Tapping on the "Exercises" button, the list of available exercises is shown. Once the student selects the exercise corresponding to the object he/she wants to model, the application provides an instruction view that resumes the basic concepts necessary to use the app (Fig. 5).

Then, the camera input is shown and the student has to frame the reference image, as for the ARViewer app. Once the target is recognized, the app displays an object and other 3-D assets that are relevant such as colored axes, edges, profiles, surfaces, and solids (Fig. 6).

The user interface displays as flat 2D elements the question in the top bar of the application and possible answers as buttons on the bottom of the view. The total points earned for the current exercise is displayed on the left, since each exercise consists of multiple questions. Each question corresponds to a step of the modeling process and it depends on the specific object: the purpose of these questions is to let the students verify the effect of the main Rhino's operators (extrude, loft, sweep, revolve, and the other commands to draw curves and surfaces). Moreover, they are solicited to consider the applicability of these operators. Fig. 6 shows an example: Rhinoceros provides different arcs to connect two curves and students are asked for selecting the most appropriate one to implement the blue segment; answers correspond to different types of arc. The students have a given time to provide an answer without getting a time-based penalty: this feature is used both to provide a point bonus for students that answer quickly and to avoid students searching for an answer online. If a wrong answer is selected, ten points are subtracted from the total score, and the student is invited to retry. Once the student provides the correct answer, he/she is asked to perform the given step using Rhinoceros (Fig. 7). Even if negative rewards might reduce long-term engagement and motivation [61], time-based and wrong answer penalties aim to train students to handle the pressure, thus emulating the exam condition.

A timer displays the maximum time to perform the modeling step, then the student should tap the screen to move on to
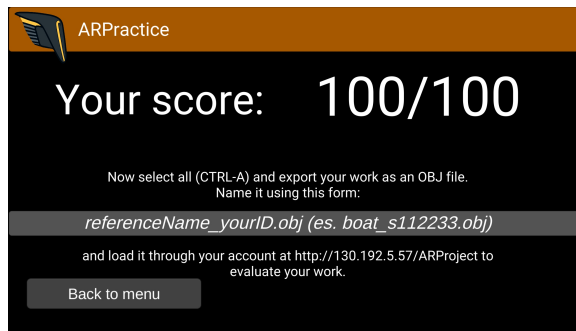
Fig. 8. The student is asked to upload the final model to the web portal.

Fig. 9. List of available reference models (left) and a 3-D model displayed over the reference image (right).

the next step of the exercise. If the countdown is completed and the student did not provide the right answer, a time-based penalty is applied to the total score. After answering the last question, the points earned for the current exercise are saved in a database and the total score is updated too. The student is then asked to upload his/her model to the web platform (Fig. 8): this allows the student to obtain the modeling score through comparison with the reference model and to interact with the teacher by comments.

The ARViewer app allows the students to view through AR a 3-D model, enabling the students to visually explore both reference models provided by the teacher and all the other public uploaded objects. This utility should enhance and simplify the process of 3-D shape understanding, which is a core step in the process of modeling by example. The students may benefit of the ARViewer in three ways:

- before performing an exercise for a given object through the ARPractice app;
- after completing the exercise to visually compare their model to the reference one;
- at the same time, they model an object through Rhinoceros without the assistance of the ARPractice app, when they are confident enough.

Once started, the app asks the student to choose an object to be displayed: a model from the references list or one from the list of public objects can be selected (Fig. 9 left).

After having chosen an object from a list, the student has to frame the reference target to initialize the tracking system. Afterwards, the model is loaded and displayed over the reference image (Fig. 9 right).

Two sliders allow the student to scale up/down the object and to change the location along the axis orthogonal to the target. Since the object is static respect to the reference image, moving either the camera or the reference image allows the student to visualize the model from different points of view.

IV. EVALUATION

Twelve volunteers have been involved in a preliminary test phase; they did not receive any form of compensation. Participants gave written informed consent in accordance with the Declaration of Helsinki. All tests have been conducted in compliance with the ethical code defined by the article 2, paragraph 4 of the Italian law 240, issued on the 30 December 2010.
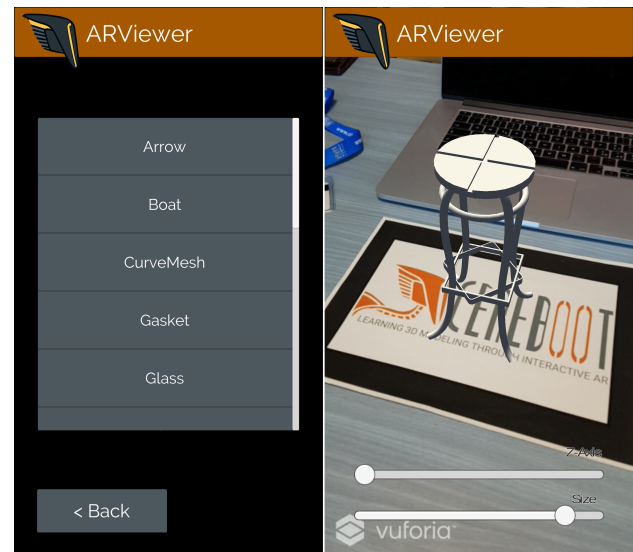
Students uploaded about 100 objects (considering both models generated by following the guided exercises of the ARPractice app and models generated to solve assignments proposed by the teacher); therefore, each student uploaded on the average 8 objects. All the objects have been commented by the teacher and some of them have been uploaded several times (replacing the previous submission) in order to accomplish specific teacher's requirements aimed to improve the similarity of submitted shapes with reference ones. Just one object has been labeled as public and students did not exchange comments.

Two different evaluations have been performed. The first one aims to assess objective parameters; in particular, the mark of the exam and the percentage of students able to pass the exam have been considered. The second evaluation is related to subjective parameters concerning the user satisfaction of the AR apps and the web portal.

All volunteers passed the exam within the current academic year and their marks ranged from 23 to 29 (marks are in thirty and 30 cum laude is assigned to outstanding exams). On the other hand, if the remaining 66 students of the class are considered, only the 70% of them passed the exam. In order to statistically analyze the exam marks, a two-tailed t-test ($p = 0.05$) with unequal variance has been performed on the average values. The null hypothesis H_0 is that there is no difference between performance of students using the proposed framework F and those who do not use it, $H_0 : \mu_F = \mu_{NoF}$. The alternative hypothesis H_1 is that one of the means is different. The p value obtained is equal to 0.018, therefore H_0 can be reject.

An effect size d has been also computed as in [37] by using the formula:

$$d = \frac{\mu_F - \mu_{NoF}}{\sigma} \quad (2)$$

where σ is the pooled standard deviation computed as:
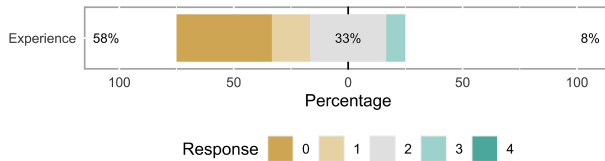
$$\sigma = \frac{\sigma_F + \sigma_{NoF}}{2} \quad (3)$$

Fig. 10. The bar chart shows the user experience with AR applications before using the ARPratice and ARViewer apps.

The calculated effect size is based on Cohen's recommendation, that is, an effect size of 0.8 or higher is considered large, around 0.5 is considered moderate, and around 0.2 is considered small. In this case, $\sigma_F = 2.016$, $\sigma_{NoF} = 3.389$, $\mu_F = 26.692$ and $\mu_{NoF} = 24.174$. The effect size can be computed as: $d = 0.93$, thus indicating that the proposed solution has a high impact on the students' performance.

The proposed system was also evaluated by an online questionnaire organized by four sections. The first section consists of general questions aimed at classify the user: age (18-22) and experience with AR applications were asked. As shown in Fig. 10, on an Likert-type scale from 0 to 4, with 0 meaning never and 4 everyday, only 1 users out of 12 gave a score of 3, whereas the other answers ranged between 0 and 2, with a median value of 1. Thus, the users who tested the applications had a few experience in using AR apps.

The second section of the questionnaire was aimed at evaluating the ARProject web portal. It consists of a standardized, 20-statement questionnaire, the WAMMI (Website Analysis and MeasureMent Inventory) [62], a renowned questionnaire developed to measure websites' user satisfaction. The questionnaire includes both positive and negative assertions regarding five characteristics: attractiveness, controllability, efficiency, helpfulness, and learnability. Users express their agreement with the sentences using a Likert-type scale from 0 to 4, with 0 meaning completely disagree and 4 completely agree. Fig. 11 shows through a bar chart the scores for each sentence of the questionnaire (questions of the WAMMI questionnaire have been summarized on the left). The scores for the negative sentences have been mirrored in order to represents all the positive scores with green bars and the negative ones with yellow bars. Overall, the users provided a positive feedback: twelve assertions out of twenty received a positive evaluation from more than 80% of the students, and the median score of 6 statements is equal to 4. Fig. 12 resumes the same scores grouped by category. The learnability score is the lowest one, probably due to the high number of features and views provided by the website, together with the lack of a video tutorial. The attractiveness was evaluated positively by slightly under 80% of users, whereas more than 80% of them provided a positive score for controllability and helpfulness.

The other sections of the questionnaire were aimed at evaluating the two AR apps. They consist of a standardized, 16-statement questionnaire, the HARUS (Handheld Augmented Reality Usability Scale) [63]: this questionnaire has been proven to have a strong correlation with the renowned SUS (System Usability Scale) [64] and obtained a Cronbach's alpha between 0.7 and 0.9, indicating a good internal consistency.
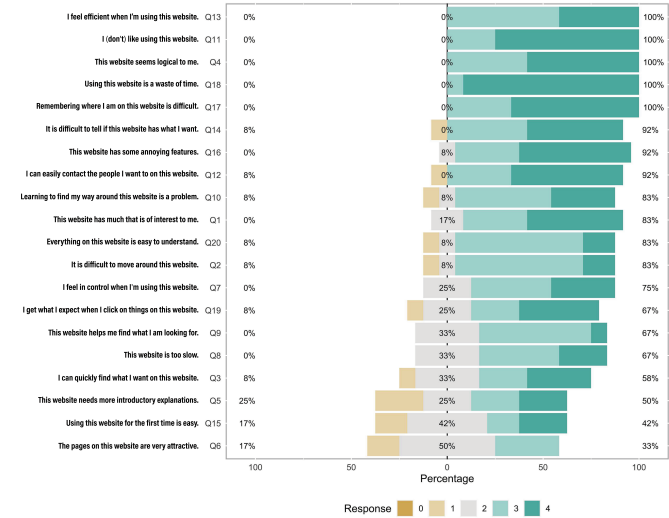

Fig. 11. The bar chart shows the scores for each sentence of the Wammi questionnaire. The size of the bars represents the number of answers for each value. The percentage values represent the number of positive (green), neutral (grey) or negative (yellow) answers.
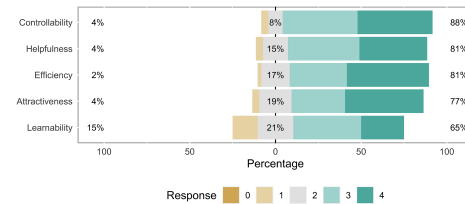

Fig. 12. The bar chart shows the scores for each category of the Wammi questionnaire. The size of the bars represents the number of answers for each value. The percentage values represent the number of positive (green), neutral (grey) or negative (yellow) answers.

The questionnaire includes both positive and negative assertions regarding two characteristics: comprehensibility and manipulability. The users express their agreement with the sentences using a Likert-type scale from 0 to 6, with 0 meaning completely disagree and 6 completely agree.

Fig. 13 and Fig. 15 show the scores for each sentence of the questionnaire, for the ARViewer and for the ARPractice app, respectively (questions of the HARUS questionnaire have been summarized on the left of Fig. 13). The scores for the negative sentences have been mirrored: positive scores are represented by green bars whereas negative scores by yellow bars. Fig. 14 and Fig. 16 resume the scores grouped by category.

The users provided a quite positive feedback for both the apps: 9 assertions out of 16 received a positive response from more than 70% of the students, whereas the median score of statements 7 and 10 is equal or greater than 5. The two applications received a similar number of positive scores; however, the ARPractice received a higher number of neutral answer than ARViewer. For the ARViewer app, both comprehensibility and manipulability were evaluated positively, respectively by the 70% and by the 68% of the users, and the median value of both categories is greater than 4. The ARPractice app was evaluated slightly better than ARViewer, with the 70% of positive scores and a median value of 5
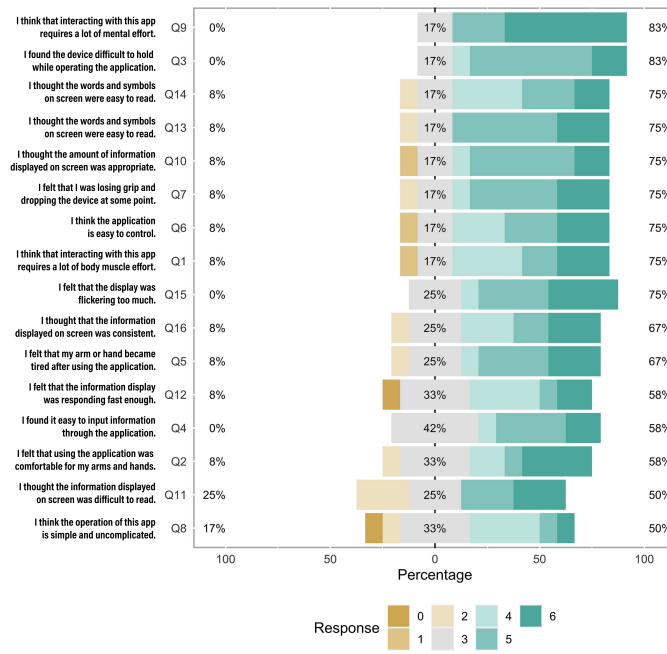
Fig. 13. The bar chart shows the scores for each sentence of the ARViewer questionnaire. The size of the bars represents the number of answers for each value. The percentage values represent the number of positive (green), neutral (grey) or negative (yellow) answers.
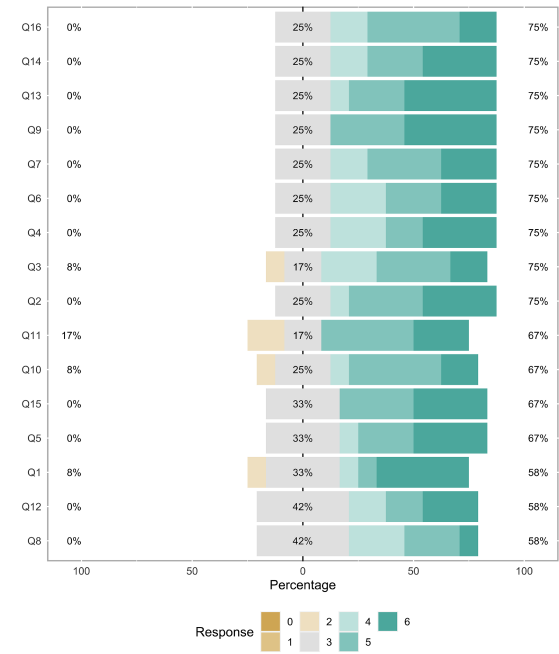

Fig. 15. The bar chart shows the scores for each sentence of the ARPractice questionnaire. The size of the bars represents the number of answers for each value. The percentage values represent the number of positive (green), neutral (grey) or negative (yellow) answers.
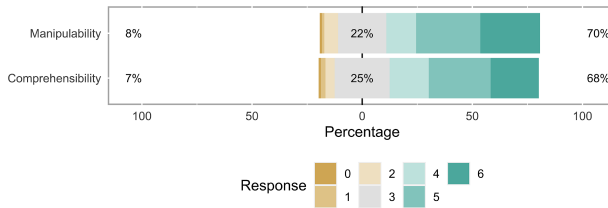

Fig. 14. The bar chart shows the scores for each category of the ARViewer questionnaire. The size of the bars represents the number of answers for each value. The percentage values represent the number of positive (green), neutral (grey) or negative (yellow) answers.
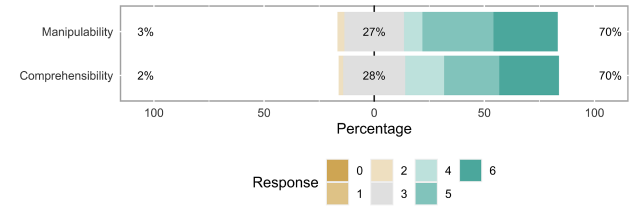

Fig. 16. The bar chart shows the scores for each category of the ARPractice questionnaire. The size of the bars represents the number of answers for each value. The percentage values represent the number of positive (green), neutral (grey) or negative (yellow) answers.

for both manipulability and comprehensibility. It is relevant to notice that both categories present a consistent number of neutral answers, whereas less than 10% of the answers were negative in both cases.

A separate assessment of the web portal and the AR apps is not easy as the effect size d computed by the formula 2 considers the framework as a whole. On the other hand, subjective feedback show that a slight preference has been assigned to the web portal. The web portal allows students to simulate exam sessions with evaluation; on the other hand, AR apps can be difficult to use for students without a prior knowledge of AR technologies. Although AR apps should be intuitive, more specific instructions (e.g., video tutorials) should be provided to train students in using ARViewer and ARPractice.

Even if the feedback gathered from volunteer students can be affected by self-selection bias and social desirability bias, this preliminary test phase was positive and the proposed tools improved learning; on the other hand, a most detailed SWOT

analysis is necessary to understand further potentialities as well as weaknesses and possible threats that these tests outlined:

- Strengths: AR improves the understanding of 3-D objects and modeling techniques can be directly related to shapes to be modeled; moreover, an immediate feedback allows students to identify problems and consolidate their knowledge. AR is much more engaging than a traditional textbook and the gamification mechanism can stimulate a positive competition among students.
- Weaknesses: Students could feel pressured to make their models public, thus frustrating all attempts to activate a discussion among peers. More attractive reward forms should be implemented to encourage students in publishing their works and share their opinions. Although provided tools do not require special skills, some students might be scared of new technologies and a video tutorial, which shows how to use the framework, should be provided. Moreover, volunteers are usually highly motivated

students that obtain good marks, therefore results need further validation.

- Opportunities: Preliminary results clearly show the potential of the proposed framework; students should be involved in a virtuous circle that can enable them to help and stimulate each other. Students might also propose reference models according their interests and also other courses (e.g., rapid prototyping) might take advantage from a community of users ready to exchange experiences and share resources.

- Threats: Students can take advantage from this framework even if they interact only with the teacher (this is proved by preliminary results), but there are two potential problems. The first one is an excessive sense of security; positive assessments when uploading models do not automatically guarantee positive marks at the exam. This is mainly due to the time limitation of the exam. The second issue is an additional workload for the teacher that has to timely maintain both the web portal and the ARPractice app, thus stimulating students to face always new and stimulating exercises.

V. CONCLUSION AND FUTURE WORK

This study proposed a framework to support design students of 3-D modeling courses during self-study. Specifically, two AR apps and a web portal are provided; the AR apps allow students both to visualize 3-D shapes and to perform a set of guided exercises concerning basic modeling techniques. On the other hand, the web portal allows students to upload their own objects and to receive an automatic feedback. Moreover, students can exchange comments with the teacher and also with the other students if uploaded models are labeled as public.

An evaluation of the framework considered both objective and subjective parameters. The objective evaluation considered the effect size on the final mark obtained by students and it was equal to 0.93 that represents a large impact on students' performance. Subjective evaluation separately considered the AR apps and the web portal: a positive evaluation was obtained with a slight preference for the web portal. Even if twelve volunteers are not sufficient to consider gathered results as definitive the feedback of this experimental phase is encouraging and large scale experiments are planned.

The framework will be opened to all students for the academic year 2021/2022 and some tutorials will be added to train users. Moreover, a new mechanism of rewarding will be implemented to foster students to make public their uploaded models, thus stimulating a much more extensive and articulated discussion among peers. This approach gives students two different advantages. The first one is the possibility to learn that their work will be offered to the public in the future, so that practicing the idea to be evaluated by others about something that those others are not culturally prepared for is a good training exercise. This can be precisely useful to help students to overcome their emotional conditions of doubt or annoyance. The second is the reverse-design process update that an open assessment can offer. Moreover, the two

AR apps will be also deployed for the Microsoft Hololens 2 glasses in order to investigate (considering a restricted number of students) the impact of a different interface that allows users to directly manipulate 3D objects without continuously switching between PC and handheld device.

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REFERENCES

[1] M. Gaiani, *La rappresentazione riconfigurata*. Edizioni POLI.design (in Italian), 2006.

[2] Robert McNeel & Associates, Rhinoceros 3D, 2021. Accessed: Feb. 26, 2021. [Online]. Available: https://www.rhino3d.com/

[3] M. Billinghurst and A. Duenser, "Augmented reality in the classroom," *Computer*, vol. 45, no. 7, pp. 56–63, Jul. 2012, doi: 10.1109/MC.2012.111.

[4] G. Chang, P. Morreale, and P. Medicherla, "Applications of augmented reality systems in education," in *Proc. 21st Society for Information Technology & Teacher Education Int. Conf.* (SITE'10), Waynesville, NC, USA, Mar. 29–Apr. 2, 2010, pp. 1380–1385.

[5] K. Lee, "Augmented reality in education and training," *TechTrends*, vol. 56, no. 2, pp. 13–21, Mar. 2012, doi: 10.1007/s11528-012-0559-3.

[6] T. Suselo, B. C. Wünsche, and A. Luxton-Reilly, "Mobile augmented reality as a teaching medium in an introductory computer graphics course," in *Proc. 6th Int. Conf. Learning and Teaching in Computing and Engineering* (LaTICE'18), Auckland, New Zealand, Apr. 19—22, 2018, pp. 72–76, doi: 10.1109/LaTICE.2018.000-3.

[7] J. Petrović, D. Tralić, and P. Pale, "Learning benefits of online formative self-assessments," in *Proc. 57th Int. Symp. ELMAR* (ELMAR'15), Zadar, Croatia, Sep. 28–30, 2015, pp. 243–246, doi: 10.1109/ELMAR.2015.7334538.

[8] T. Trust, R. W. Maloy, and S. Edwards, "Learning through making: Emerging and expanding designs for college classes," *TechTrends*, vol. 62, no. 1, pp. 19–28, Jan. 2018, doi: 10.1007/s11528-017-0214-0.

[9] R. T. Azuma, "A survey of augmented reality," *Presence*, vol. 6, no. 4, pp. 355–385, Aug. 1997, doi: 10.1162/pres.1997.6.4.355

[10] E. Z. Barsom, M. Graafland, and M. P. Schijven, "Systematic review on the effectiveness of augmented reality applications in medical training," *Surgical Endoscopy*, vol. 30, no. 10, pp. 4174–4183, Oct. 2016, doi: 10.1007/s00464-016-4800-6.

[11] C. Kamphuis, E. Barsom, M. Schijven, and N. Christoph, "Augmented reality in medical education?" *Perspectives Med. Educ.*, vol. 3, no. 4, pp. 300–311, Sep. 2014, doi: 10.1007/s40037-013-0107-7.

[12] A. M. Borrero and J. A. Márquez, "A pilot study of the effectiveness of augmented reality to enhance the use of remote labs in electrical engineering education," *J. Sci. Educ. & Technol.*, vol. 21, no. 5, pp. 540–557, Oct. 2012, doi: 10.1007/s10956-011-9345-9.

[13] F. Liarokapis *et al.*, "Web3D and augmented reality to support engineering education," *World Trans. Eng. Technol. Educ.*, vol. 3, no. 1, pp. 11–14, Jan. 2004.

[14] F. Abdullah, M. H. B. Kassim, and A. N. Z. Sanusi, "Go virtual: Exploring augmented reality application in representation of steel architectural construction for the enhancement of architecture education," *Adv. Sci. Lett.*, vol. 23, no. 2, pp. 804–808, Feb. 2017, doi: 10.1166/ASL.2017.7449.

[15] D. Fonseca, S. Villagrasa, N. Martí, E. Redondo, and A. Sánchez, "Visualization methods in architecture education using 3D virtual models and augmented reality in mobile and social networks," *Procedia Soc. Behav. Sci.*, vol. 93, pp. 1337–1343, Oct. 2013, doi: 10.1016/j.sbspro.2013.10.040.

[16] Y.-C. Chen, "A study of comparing the use of augmented reality and physical models in chemistry education," in *Proc. 2006 ACM Int. Conf. Virtual Reality Continuum and Its Applications* (VR-CIA'06), Hong Kong, China, Jun. 14–17, 2006, pp. 369–372, doi: 10.1145/1128923.1128990.

[17] M. Núñez, R. Quirós, I. Núñez, J. B. Carda, E. Camahort, and J. Mauri, "Collaborative augmented reality for inorganic chemistry education," in *Proc. 5th WSEAS/IASME Int. Conf. on Mathematics and Computers in Science and Engineering* (EE'08), Heraklion, Greece, Jul. 22-24, 2008, vol. 5, pp. 271–277.

[18] A. Estapa and L. Nadolny, "The effect of an augmented reality enhanced mathematics lesson on student achievement and motivation," *J. STEM Educ.: Innov. & Res.*, vol. 16, no. 3, Aug.–Sep. 2015.

[19] H. Kaufmann and D. Schmalstieg, "Mathematics and geometry education with collaborative augmented reality," *Comput. & Graph.*, vol. 27, no. 3, pp. 339–345, Jun. 2003, doi: 10.1016/S0097-8493(03)00028-1.

[20] A. Dünser, L. Walker, H. Horner, and D. Bentall, "Creating interactive physics education books with augmented reality," in *Proc. 24th Australian Computer-Human Interaction Conf.* (OzCHI'12), Melbourne, Australia, Nov. 26–30, 2012, pp. 107–114, doi: 10.1145/2414536.2414554.

[21] H. Kaufmann and B. Meyer, "Simulating educational physical experiments in augmented reality," in *Proc. ACM SIGGRAPH Asia 2008 Educators Programme* (SIGGRAPH Asia'08), Singapore, Dec. 10–13, 2008, Paper no. 3, doi: 10.1145/1507713.1507717.

[22] B. E. Shelton and N. R. Hedley, "Using augmented reality for teaching earth-sun relationships to undergraduate geography students," in *Proc. 1st IEEE Int. Workshop Agumented Reality Toolkit,* Darmstadt, Germany, Sep. 29, 2002, Paper no. 2, doi: 10.1109/ART.2002.1106948.

[23] Z. Turan, E. Meral, and I. F. Sahin, "The impact of mobile augmented reality in geography education: Achievements, cognitive loads and views of university students," *J. Geography Higher Educ.*, vol. 42, no. 3, pp. 427–441, Jul.–Sep. 2018, doi: 10.1080/03098265.2018.1455174.

[24] J.-C. Yen, C.-H. Tsai, and M. Wu, "Augmented reality in the higher education: Students' science concept learning and academic achievement in astronomy," *Procedia - Social Behav. Sci.*, vol. 103, no. 26, pp. 165–173, Nov. 2013, doi: 10.1016/j.sbspro.2013.10.322.

[25] J. Zhang, Y.-T. Sung, H.-T. Hou, and K.-E. Chang, "The development and evaluation of an augmented reality-based armillary sphere for astronomical observation instruction," *Comput. & Educ.*, vol. 73, pp. 178–188, Apr. 2014, doi: 10.1016/j.compedu.2014.01.003.

[26] A. M. McNamara, "Enhancing art history education through mobile augmented reality," in *Proc. 10th Int. Conf. Virtual Reality Continuum Its Applications in Industry* (VRCAI'11), Hong Kong, China, Dec. 11–12, 2011, pp. 507–512, doi: 10.1145/2087756.2087853.

[27] K. Schrier, "Using augmented reality games to teach 21st century skills," in *Proc. ACM SIGGRAPH 2006 Educators program* (SIGGRAPH'06), Boston, MA, USA, Jul. 30–Aug. 3, 2006, Paper no. 15, doi: 10.1145/1179295.1179311.

[28] Z. Noh, M. S. Sunar, and Z. Pan, "A review on augmented reality for virtual heritage system," in *Proc. Int. Conf. Technologies for E-learning and Digital Entertainment* (Edutainment'09), Banff, AB, Canada, Aug. 9–11, 2009, pp. 50–61, doi: 10.1007/978-3-642-03364-3_7.

[29] V. Vlahakis *et al.*, "Archeoguide: An augmented reality guide for archaeological sites," *IEEE Comput. Graph. Appl.*, vol. 22, no. 5, pp. 52–60, Sep.–Oct. 2002, doi: 10.1109/MCG.2002.1028726.

[30] J. Chow, H. Feng, R. Amor, and B. C. Wünsche, "Music education using augmented reality with a head mounted display," in *Proc. 14th Australasian User Interface Conf. - Volume 139* (AUIC'13), Melbourne, Australia, Jan. 29–Feb. 1, 2013, pp. 73–79.

[31] D. Smith,"Augmented reality in art education," M.S. capstone paper, Educ. Technol. Program, Univ. Arizona, Sierra Vista, AZ, USA, 2016. [Online]. Available: http://hdl.handle.net/10150/621860

[32] F. Liarokapis, "Using Activity Led Learning for Teaching Computer Graphics Principles Through Augmented Reality," in *Proc. European Association for Computer Graphics: Education Papers* (EG'17), Lyon, France, Apr. 24–28, 2017, doi: 10.2312/eged.20171025.

[33] T. Suselo, B. C. Wünsche, and A. Luxton-Reilly, "Using mobile augmented reality for teaching 3D transformations," in *Proc. 52nd ACM Technical Symp. on Computer Science Education* (SIGCSE'21), Virtual Event USA, Mar. 13–20, 2021, pp. 872–878, doi: 10.1145/3408877.3432401.

[34] M. Abdinejad, B. Talaie, H. S. Qorbani, and S. Dalili, "Student perceptions using augmented reality and 3D visualization technologies in chemistry education," *J. Sci. Educ.& Technol.*, vol. 30, no. 1, pp. 87–96, Feb. 2021, doi: 10.1007/s10956-020-09880-2.

[35] R. I. Barraza Castillo, V. G. Cruz Sánchez, and O. O. Vergara Villegas, "A pilot study on the use of mobile augmented reality for interactive experimentation in quadratic equations," *Math. Problems Eng.*, vol. 2015, 2015, Art no. 946034, doi: 10.1155/2015/946034.

[36] S. Cai, C. Liu, T. Wang, E. Liu, and J.-C. Liang, "Effects of learning physics using augmented reality on students' self-efficacy and concep-

[37] M. E. C. Santos, A. Chen, T. Taketomi, G. Yamamoto, J. Miyazaki, and H. Kato, "Augmented reality learning experiences: Survey of prototype design and evaluation," *IEEE Trans. Learn. Technol.*, vol. 7, no. 1, pp. 38–56, Jan.–Mar. 2014, doi: 10.1109/TLT.2013.37.

[38] I. Radu, "Augmented reality in education: a meta-review and cross-media analysis," *Pers. Ubiquit. Comput.*, vol. 18, no. 6, pp. 1533–1543, Jan. 2014, doi: 10.1007/s00779-013-0747-y

[39] Y.-C. Chen, H.-L. Chi, W.-H. Hung, and S.-C. Kang, "Use of tangible and augmented reality models in engineering graphics courses," *J. Prof. Issues Eng. Educ. Pract.*, vol. 137, no. 4, pp. 267–276, Oct. 2011, doi: 10.1061/(ASCE)EI.1943-5541.0000078.

[40] M. Ivanova and G. Ivanov, "Communications in computer and information science: Using marker augmented reality technology for spatial space understanding in computer graphics," in *Proc. Digital Inf. and Comm. Technol. and Its Applications* (DICTAP'11), Dijon, France, Jun. 21–23, 2011, pp. 368–379, doi: 10.1007/978-3-642-21984-9_32.

[41] H. Kaufmann, "Construct3D: An augmented reality application for mathematics and geometry education," in *Proc. 10h ACM Int. Conf. Multimedia* (MULTIMEDIA'02), Juan-les-Pins, France, Dec. 1–6, 2002, pp. 656–657, doi: 10.1145/641007.641140.

[42] P. H. Jones, "Systemic design principles for complex social systems," in *Social systems and design*. Springer, Tokyo, Japan, 2014, pp. 91–128, doi: 10.1007/978-4-431-54478-4_4.

[43] P. Ciuccarelli, *Design open source: Dalla partecipazione alla progettazione in rete*. Pitagora Editrice (in Italian), 2008.

[44] G. A. Brown, J. Bull, and M. Pendlebury, *Assessing Student Learning in Higher Education*. London, U.K.: Routledge, 1997.

[45] D. McConnell, "E-learning groups and communities?," *Brit. J. Educ. Technol.*, vol. 37, no. 6, pp. 973–990, Nov. 2006, doi: 10.1111/j.1467-8535.2006.00660_13.x.

[46] J. W. Gikandi, D. Morrow, and N. E. Davis, "Online formative assessment in higher education: A review of the literature," *Comput. & Educ.*, vol. 57, no. 4, pp. 2333–2351, Dec. 2011, doi: 10.1016/j.compedu.2011.06.004.

[47] K. Wilson, C. Boyd, L. Chen, and S. Jamal, "Improving student performance in a first-year geography course: Examining the importance of computer-assisted formative assessment," *Comput. & Educ.*, vol. 57, no. 2, pp. 1493–1500, Sep. 2011, doi: 10.1016/j.compedu.2011.02.011.

[48] L. de Marcos *et al.*, "An experiment for improving students performance in secondary and tertiary education by means of m-learning auto-assessment," *Comput. & Educ.*, vol. 55, no. 3, pp. 1069–1079, Nov. 2010, doi: 10.1016/j.compedu.2010.05.003.

[49] M. Ćukušić, Ž. Garača, and M. Jadrić, "Online self-assessment and students' success in higher education institutions," *Comput. & Educ.*, vol. 72, pp. 100–109, Mar. 2014, doi: 10.1016/j.compedu.2013.10.018.

[50] B. C. Wünsche *et al.*, "Automatic assessment of OpenGl computer graphics assignments," in *Proc. 23rd Annu. ACM Conf. Innovation and Technology in Computer Science Education* (ITiCSE'18), Larnaca, Cyprus, Jul. 2–4, 2018, pp. 81–86, doi: 10.1145/3197091.3197112.

[51] B. C. Wünsche *et al.*, "CoderunnerGl-an interactive web-based tool for computer graphics teaching and assessment," in *Proc. 2019 Int. Conf. on Electronics, Information, and Communication* (ICEIC'19), Auckland, New Zealand, Jan. 22–25, 2019, pp. 1–7, doi: 10.23919/ELINFO-COM.2019.8706402.

[52] D. H. Baxter and M. J. Guerci, "Automating an introductory computer aided design course to improve student evaluation," in *Proc. 2003 American Society for Engineering Education Annu. Conf. & Expos.* (ASEE'03), Nashville, TN, USA, Jun. 22–25, 2003, pp. 8.258.1–8.258.9, doi: 10.18260/1-2–11479.

[53] A. Sanna, F. Lamberti, G. Paravati, and C. Demartini, "Automatic assessment of 3D modeling exams," *IEEE Trans. Learn. Technol.*, vol. 5, no. 1, pp. 2–10, Jan.–Mar. 2012, doi: 10.1109/TLT.2011.4.

[54] K. Jaakma and P. Kiviluoma, "Auto-assessment tools for mechanical computer aided design education," *Heliyon*, vol. 5, no. 10, 2019, Art no. e02622. doi: 10.1016/j.heliyon.2019.e02622.

[55] J. Hattie, *Visible learning for teachers: Maximizing impact on learning*. Routledge, London, U.K., 2011.

[56] B. Frank, N. Simper, and J. Kaupp, "Formative feedback and scaffolding for developing complex problem solving and modelling outcomes," *Eur. J. Eng. Educ.*, vol. 43, no. 4, pp. 552–568, Oct.–Dec. 2018, doi: 10.1080/03043797.2017.1299692.

[57] B. Hodgkinson, C. Lutteroth, and B. Wünsche, "glGetFeedback — Towards automatic feedback and assessment for OpenGl 3D modelling assignments," in *Proc. 2016 2016 Int. Conf. Image and Vision Computing

New Zealand (IVCNZ'16), Palmerston North, New Zealand, Nov. 21–22, 2016, pp. 1–6, doi: 10.1109/IVCNZ.2016.7804418.

[58] A. E. Kay, J. Hardy, and R. K. Galloway, "Learning from peer feedback on student-generated multiple choice questions: Views of introductory physics students," *Phys. Rev. Phys. Educ. Res.*, vol. 14, no. 1, pp. 010119-1–010119-17, Apr. 2018, doi: 10.1103/PhysRevPhysEducRes.14.010119.

[59] Blender Online Community, Blender Foundation, 2021. Accessed: Feb. 26, 2021. [Online]. Available: https://www.blender.org/

[60] D.-Y. Chen, X.-P. Tian, Y.-T. Shen, and M. Ouhyoung, "On visual similarity based 3D model retrieval," *Comput. Graph. Forum*, vol. 22, no. 3, pp. 223–232, Sep. 2003, doi: 10.1111/1467-8659.00669.

[61] P. Denny, "The effect of virtual achievements on student engagement," in *Proc. SIGCHI Conference Human Factors in Computing Systems* (CHI'13), Paris, France, Apr. 27–May 2, 2013, pp. 763—-772, doi: 10.1145/2470654.2470763.

[62] J. Kirakowski and B. Cierlik, "Measuring the Usability of Web Sites," *Proc. of the Human Factors and Ergonomics Society Annual Meeting*, vol. 42, no. 4, pp. 424–428, Oct. 1998, doi: 10.1177/154193129804200405.

[63] M. E. C. Santos, J. Polvi, T. Taketomi, G. Yamamoto, C. Sandor, and H. Kato, "Toward standard usability questionnaires for handheld augmented reality," *IEEE Comput. Graph. Appl.*, vol. 35, no. 5, pp. 66–75, Sep.–Oct. 2015, doi: 10.1109/MCG.2015.94.

[64] J. Brooke, "SUS: A 'quick and dirty' usability scale," in *Usability Evaluation in Industry*, W. J. Patrick, B. Thomas, I. L. McClelland, and B. Weerdmeester, Eds., London, U.K.: CRC Press, 1996, pp. 189–194.

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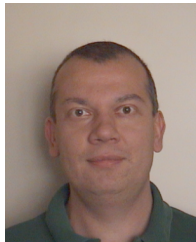
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