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Novel Hands-on Product-design Module for Online, Large-enrollment FYE Courses

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Introduction

Engineering design principles and processes are foundational concepts across the engineering disciplines [1]–[7]. From a professional development perspective, open-ended design projects, which are frequently conducted in team-based settings, offer students a scaffolded apprenticeship with opportunities to engage in collaborative planning and work akin to that of the workforce. From a pedagogical perspective, they require students to think critically about a wide range of engineering concepts and to complete a variety of practical tasks related to learning objectives. Team-based learning through design projects provides students with technical and non-technical mastery experiences in their disciplines [8], [9], supports the development of collaboration and communication skills for working with other professionals, and engages novice engineers in higher levels of thinking and problem-solving than possible through theory-based classes alone [1], [10]. For all of these reasons, team-based engineering design experiences are heavily utilized in engineering undergraduate programs, with the importance of these experiences being reinforced by ABET as a part of required student outcomes [11].

First year experience (FYE) engineering courses are frequently used to orient students to the engineering design process and establish the norms for process, performance, and collaboration that will be expected in latter design experiences within particular engineering disciplines. Several challenges arise when designing and implementing team-based engineering design projects in FYE courses. First, the technical concepts involved must be appropriately scaled to the novice level. Mechanically-oriented product design projects are particularly popular in FYE courses for this reason, as they leverage students' existing content knowledge of geometry and physical science concepts from high school. Second, logistical requirements of the project, e.g., required materials or software, and instructor supervision or training, must fit within the constraints of the FYE course. Although the product design process can culminate in either a physical or virtual prototype (i.e., "paper design"), hands-on fabrication of a physical prototype has been shown to improve basic engineering skills, viz. spatial visualization, and increase student interest and retention in the discipline. FYE courses are frequently taught in large-enrollment settings, which adds logistical complexity to supplying and supervising hands-on prototyping across a large number of students. Lastly, engineering design challenges must be thoughtfully scaffolded in FYE courses to help novice students navigate complex, longer-term projects in a team-based setting. Prior work by our group and others [Authors 2018, 2019, citation redacted for review] have shown unequal distribution of tasks on team-based projects, caused in part by differences in self-efficacy and prior experiences. This effect can be mitigated through scaffolded assignments, regular peer evaluations, and more frequent opportunities for individual and team-based self-reflection [2], [8], [12].

The transition to online instruction due to the COVID-19 pandemic this past year only compounded the pre-existing logical and pedagogical challenges associated with engineering design in FYE courses. The most pressing challenge for these courses in an online-only environment was ensuring students access to essential equipment and materials to design and construct a physical prototype. In general, programs responded to this challenge in one of three ways: (1) abandoning physical prototyping for an entirely "paper design" project; (2) requiring students to purchase third party construction kits (e.g., Arduino or Vex Robotics); or (3) encouraging students to use common household items for physical prototyping. Each of these strategies has an inherent shortcoming when compared to using institutional resources, e.g., makerspaces or shops, to fabricate prototypes in a face-to-face (F2F) setting. Paper designs do not afford the same benefits as hands-on prototyping in terms of development of spatial visualization skills [13], [14] Third-party construction kits are expensive, particularly in large-enrollment settings, and may inherently restrict students' designs to those that are more aligned with the construction kit itself than the project scope. Lastly, the exclusive use of household items for prototyping raises issues of equity and access, which in turn may lead to wide differences in the quality and complexity of physical prototypes. There is a clear need for FYE engineering design curriculum that affords students an opportunity for hands-on, open-ended prototyping in an online-only setting.

In this paper, we introduce a novel hands-on, mechanically-oriented product design module, called UDGears, which could be offered with fidelity in FYE engineering courses in a completely online course setting. The UDGears curriculum was designed for a large-enrollment course format but can be scaled to fit any class size. The curriculum addresses financial, material, and student safety constraints inherent to FYE courses of any size enrollment while also presenting students with a substantive engineering challenge that addresses common FYE learning objectives. The effectiveness of the UDGears curriculum was evaluated retrospectively by comparing student performance between two consecutive years of a large-enrollment FYE course in which UDGears was offered in an online-only setting and a comparable mechanical design project was offered F2F. The curricular structure and results of this study might provide insight to similar programs at other institutions that are attempting to maintain hands-on learning experiences in FYE engineering courses, particularly during mandated online instructional periods.

Methods

UDGears Curriculum

The UDGears curriculum was designed as a multi-week, team-based design project to be embedded within a semester long (14 week), online FYE engineering course. The learning objectives for the project were as follows: (1) to apply principles of simple machines and conservation of energy; (2) to improve spatial visualization skills through creation and manipulation of 2D and 3D design; and (3) to persist through one full engineering product design cycle in developing and testing a functional prototype. As described in detail in another paper by our group at this conference [Authors 2021, pending review], the FYE course utilized a flipped instructional design for online-only delivery. Didactic content was delivered asynchronously, and active learning elements were reserved for synchronous workshops, which were held weekly via video conferencing (Zoom Video Communications, Inc.) and allowed students the opportunity to work directly with their teammates. Students were randomly assigned to teams of 5-6 individuals and remained in the same team for the duration of the semester. Students were required to complete weekly peer evaluations using CATME (Comprehensive Assessment of Team Member

Effectiveness) [15] that were used to discriminate individual from team performance on assessments.

The UDGears curriculum spanned an 7-week period in a semester-long (14 week), 2 credit hour course. Student teams were guided through a four-phase design process (Phase 1: Problem Definition, Phase 2: Concepts, Phase 3: Detailed Design, Phase 4: Design Validation) via weekly scaffolded team assignments that corresponded with the weekly didactic course content (Table 1). The initial assignments focused on user-centered research, benchmarking, and concept generation. This was followed by a four-week module on machine design that covered topics including simple machines, fits and tolerances, and 2D and 3D computer aided design. The final two weeks of the curriculum focused on design validation and technical communication skills specific to the project final deliverables. Final deliverables were a full-length engineering design report and a brief (5-minute) public slide-deck presentation.

Table 1. Fall 2020 course schedule detailing week-by-week learning objectives and related weekly team assignments.

Week	Didactic Course Content	Scaffolded Weekly Team Activity
1	Engineering product design process, benchmarking & background research	(Activity #1) Phase 1: Background Research & Benchmarking
2	User-centered research (UCR), survey design and data analysis	(Activity #2) Phase 1: Conduct Individual-level and Population-level (survey) UCR
3	Project scope, metrics, target values	(Activity #3) Phase 1: Metrics & Target Values, Draft complete Phase 1 report
4	Simple machines, conservation of energy principles, mechanical advantage	(Activity #4) Phase 2: Simple machine scavenger hunt and assembling simple machine models
5	Concept sketching, decision matrices	(Activity #5) Phase 2: Concept generation, sketching and descriptions, decision matrix for concept selection
6	Additive & subtractive manufacturing processes, 2D design principles, 2D & 3D software	(Activity #6) Phase 3: 3D mock-up of early stage prototypes, final design schematics in 2D, design calculations, submit 2D design for manufacturing
(7-12)	(Other course content)	(Offline manufacturing of prototype, mailing to student, student assembly of prototype)
13	Experimental design, design validation, descriptive statistics	(Activity #7) Phase 4: Final prototype testing, design validation, assessment of path forward

14	Professional communication, technical writing, oral presentations	Final Deliverables: Engineering design report, brief team presentation (online, with visuals)

The overarching theme for the UDGears project was inspired by a line of commercially available wooden mechanical models called UGears® (Ukidz LLC, [16]). UGears® models are entirely composed of parts that are laser-cut from thin sheets of wood (3 mm thick birch), and most product designs incorporate gear, linkage, and other simple machine components. With permission from the company, the UDGears curriculum challenged students to design a new model for the UGears® product line that specifically targeted the college market. Consistent with the UGears® product line, the UDGears designs were to be entirely laser cut from wood sheets (1/8 inch thick, birch wood), and additional design constraints were imposed on the project (Table 2) so that the final designs could be manufactured on university-owned laser cutters and mailed in standard size packaging. Constraints were also imposed on the quantity and type of mechanisms within the design to ensure a minimum level of complexity in the prototypes (see Table 2).

Table 2. Instructor-imposed design constraints and associated target values for UDGears project.

Metric	**Target Value**
Single input	One manual input, e.g., cranking or pulling
Multiple outputs	At least 2 unique outputs, with one output being out-of-phase or plane with input
Mechanically complex	At least 3 simple machine components
Materials	Design must be entirely laser cut from one 8x10 inch sheet of 1/8 thick birch wood. May also use rubber bands and string.
Minimal waste material	Smallest possible 2D envelope for laser cut pieces
Engaging	Mechanical components are visible
Appropriate	If it were a movie, it'd have a "G" to "PG" rating

The hands-on components of the UDGears project involved several additional logistical and curricular elements. During the first two weeks of the semester, students were mailed a course material packet (US Postal Service for domestic mail, FedEx for international mail) that included several small UGears® models and a custom-designed, laser-cut common components board with pre-defined gears, axles, and machine frames (Figure 1). The UGears® models were used during Phase 1 team exercises for benchmarking and user-centered research (see Table 1). The common components board was designed as part of the UDGears curriculum and featured simple mechanisms (e.g., gears, linkages, and cams) that could be combined to form various simple machines. Students assembled simple machines from the common components board during Phase 2 and Phase 3 team exercises (see Table 1), and the components of the board were repeatedly used as design examples, for instance, in calculating appropriate tolerances for press fits of components. Students could use common components pieces in their early stage prototype and final prototype designs, and they were provided with the original design files for the entire board.

Figure 1. Students were mailed a course welcome packet that included (left) several UGears® models (Ukidz LLC) that served as benchmark designs as well as (right) a custom-designed common components board that was used in Phase 2 and Phase 3 team exercises. Students could also incorporate elements from the common components board into their final UDGears design.

Student teams were guided through a series of weekly exercises to create sequentially more detailed versions of their custom UDGears design. They first created 2D paper sketches of three unique concepts and then translated these sketches into early-stage 3D prototypes that were constructed from a combination of components from the common components board (see Figure 1, right) and household items, specifically, standard cardboard, which conveniently has the same thickness (~1/8 inch) as the final laser cut components. After constructing, iterating, and documenting their early stage 3D prototypes, students began to formalize their designs for final manufacture on the laser cutter. Student teams had the choice of using either 2D vector graphics software (Inkscape v1.0) or 3D computer aided engineering design (CAD) software (SolidWorks or Autodesk Inventor). Instructor-designed quick-start tutorials, with exemplars from the UDGears project, were created and released to students asynchronously. Student teams explicitly discussed prior knowledge of 2D and 3D computer aided design (CAD) software, which was not a prerequisite for this course, before deciding as a team on which software to use for detailed design, and the 2D vector graphics package was recommended as the default option. An example UDGears design (Figure 2), created by the faculty instructor, was used to demonstrate all detailed design steps in didactic course content and weekly synchronous class sessions.

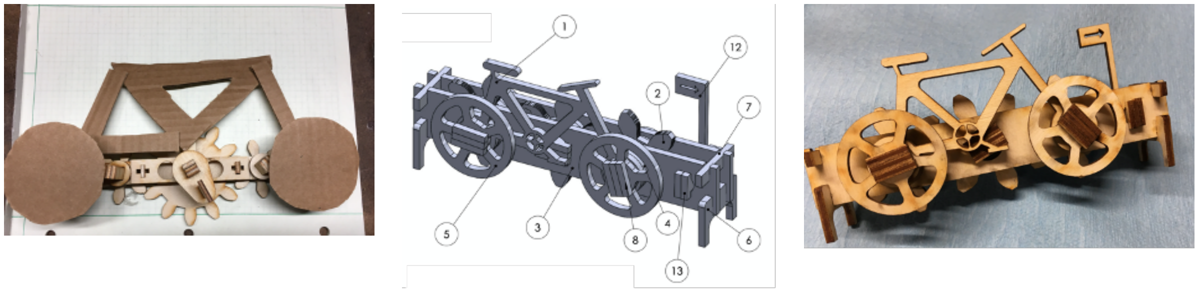

Figure 2. Example design project created by the faculty instructor and used to demonstrate all steps of the product design process. (left) early stage prototype constructed from household goods and components from the provide common components board (see Figure 1); (middle) assembly view of 3D CAD design; and (right) final laser-cut prototype.

Students UDGears prototypes were manufactured in on-campus facilities by professional staff using a standard medium-duty laser cutter (PLS6, 150 W, Universal Laser Systems). Students were required to submit their final design files as 2D vector graphic images (.svg format) by the end of the 9th week of the course, and a single prototype was mailed to a designated team member by the end of the 11th week of the course. The course schedule was adjusted to allow for this manufacturing and shipping period. Once students received their prototypes, the final didactic module and scaffolded team activity related to design validation were conducted (see Table 1).

Evaluation of UDGears Curriculum

The effectiveness of the UDGears curriculum was evaluated by comparing student performance and perceptions for the UDGears project versus a comparable, pre-existing curriculum in the same large-enrollment FYE course. The course, Introduction to Engineering, is a 2-credit hour, 14-week course taken in the first (fall) semester by all incoming engineering students across all majors at a mid-sized, research-intensive state university in the US. The course is taught in two identical, large-enrollment sections of ca. 350 students per section by two faculty co-instructors, assisted by a cadre of undergraduate teaching assistants. UDGears was administered in the Fall 2020 semester in an entirely online setting due to the COVID-19 pandemic. The prior curriculum was used in a face-to-face (F2F0 setting the preceding academic year (Fall 2019). The F2F curriculum utilized near-identical student exercises and didactic content (see Table 1) and mapped to the same course learning objectives as UDGears. F2F differed only in that it culminated in early prototyping of a mechanical system by students who were provided with light duty construction materials and tools, e.g., posterboard, dowel rods, hack saws.

UDGears and F2F curriculum were compared by examining student performance on final project deliverables and the weekly team-based activities that scaffold those final deliverables (see Table 1). All student work was graded according to the same, pre-defined rubrics [Authors, 2020, citation redacted for review] for both UDGears and F2F versions. Student scores were compared across project versions via t-test with unequal variances (JMP Pro v15). Due to the retrospective nature of this study, data on student perceptions of the project was available only for the UDGears project at the midpoint of the course. The midterm course survey had one, Likert-scale item directly related to the project as well as a free-response section. The midterm survey was distributed via Qualtrics to the students at week 6 of the semester. Descriptive statistics are presented for the survey item, as well as select student feedback from the free-response portion.

Results

In the online version of the large-enrollment FYE course, students successfully designed and assembled unique UXGear project designs (Figure 3) that were manufactured according to their specifications using on-campus resources. All but two of the 133 student teams were able to have their designs manufactured, although approximately 15% did document a disparity between their design, as conceived, and the laser-cut pieces that were manufactured according to their design plans. Per student material costs for the UDGears version of the project were $8.50 as compared to $13.25 for F2F. Final scores skewed higher on all student performance measures for the UDGears project than the F2F version (see Table 3).

Figure 3. Final prototypes of UDGears designs in the online-only, large-enrollment FYE engineering course in Fall 2020. All designs were laser-cut using university-owned equipment and mailed to students for final assembly and testing.

Table 3. Student performance measures and t-test results for UDGears and F2F team-based projects (n=651 and n=725, respectively). All outcomes are graded on a 100-point scale using common rubrics. See Table 1 for description of weekly scaffolded team activities. Final project deliverables are a full-length design report and brief oral presentation.

Project component	Mean value (standard deviation)		Effect size (difference in means)	t-statistic	DF	p-value
	UDGears	*F2F*				
Activity #1	95.2 (7.8)	91.9 (9.2)	3.3	7.2	1370.4	<.0001
Activity #2	94.2 (9.4)	91.7 (8.7)	2.5	5.0	1327.6	<.0001
Activity #3	90.9 (10.7)	85.9 (14)	5.0	7.4	1344.0	<.0001
Activity #4	93.3 (8.1)	91.5 (10.3)	1.8	3.8	1348.7	0.0002
Activity #5	95.4 (6.7)	93.1 (9.4)	2.3	5.2	1304.8	<.0001
Activity #6	94.8 (6.5)	90.8 (11.1)	4.0	8.1	1185.7	<.0001
Activity #7	93.1 (10.7)	91.6 (10.2)	1.5	2.6	1344.3	0.0086
Final Deliverables	91.6 (7.8)	84.0 (9.3)	7.4	16.5	1368.4	<.0001

Student perceptions of the UDGears project, as measured on the mid-course survey were positive. 80% of students rated the project as “Good” or “Very Good” (Figure 4), with only 3% rating as “Poor. Comments related to the project—which were not directly solicited—were uniformly positive (Table 4) and stressed the collaborative aspects of the project as well as its reinforcement of design principles.

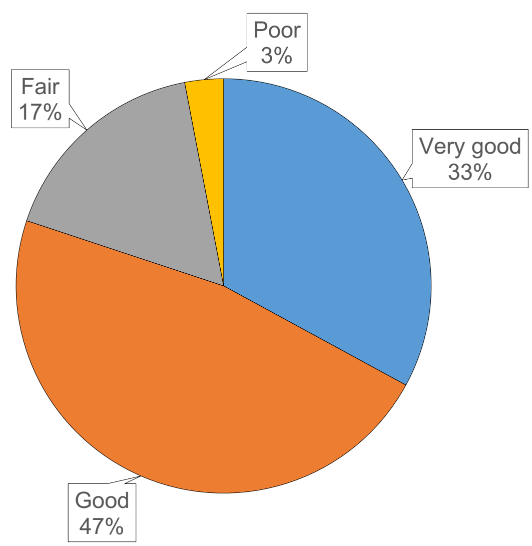

Figure 4. Results of mid-course student feedback survey for the UDGears project only. Question prompt was “Please rate the quality of the following course element(s): Group Projects”. Survey was administered at 6-weeks into the semester, so “Group Projects” refers only to UDGears project.

Table 4. Select student feedback on mid-course survey related to UDGears project only.

The project is very helpful in applying what we learn in lectures and learning to work with a team.
The U[X]ears project! It was a lot of fun and without a doubt the best part of this course. I would love to see this done every year.
The group projects are what keep me going! This is really the only chance I've gotten to actually talk to and connect with other students, and I love my team...These projects are also super exciting to me in terms of content because I'm particularly interested in mechanical engineering.
Weekly activities and the breakdown of one large project makes it seem less overwhelming.
I would like you to continue with the large group projects during the semester since it allows for building engineering skills as well as getting to know fellow first year students.
The UGears project is overall a good project for walking through a design process.

Discussion

The paper presents a novel hands-on, mechanically-oriented product design curriculum (UDGears) that was successfully deployed in a large-enrollment, online FYE engineering course. Logistical overhead for the course was no more cumbersome than for hands-on activities in F2F settings; and the new curriculum, which leveraged on-campus manufacturing resources to fabricate student prototypes, was in fact slightly more economical in terms of material costs. More importantly, student learning outcomes were not adversely affected by the transition to an online version of the project. In fact, student performance for the online (UDGears) version of the project exceeded F2F relative across all outcomes, including weekly activities and final deliveravles, although this effect may be more likely caused by curricular differences between the two project designs rather than the online vs. F2F instructional modality. Going forward, our institution intends to utilize the new UDGears module in place of the prior curriculum, even as instruction moves back to an in-person setting. There will be slight modifications to the curriculum to allow for more F2F contact between student teams, particularly during the early stage prototyping with light duty materials, as well as coordinated visits to witness final prototype manufacture in on-campus facilities.

Although this study is unique in that it demonstrates that hands-on engineering design projects can be conducted in online-only settings, our findings relative to student performance outcomes are consistent with the literature. Active learning and PBL strategies have been implemented with fidelity in online courses and have been shown to improve student engagement and persistence [17], [18]. Furthermore, a "flipped" approach to classroom instruction, with didactic content being viewed asynchronously and synchronous class time being utilized for team-based activities, has been shown by Baughman et al. [8] to lead to higher overall student satisfaction than traditional course structures. Taken together, the access to PBL activities and opportunity for dedicated collaboration time may contribute to our observed high levels of satisfaction and student performance with the UDGears project.

There are several strengths and some caveats to the work presented in this paper that should be addressed. Restrictions due to the COVID-19 pandemic provided a unique opportunity to retrospectively compare hands-on engineering design curriculum across two delivery modalities. Both the UDGears and F2F projects were designed to meet the same learning objectives and evaluated student performance according to previously established, well defined student rubrics [Authors, 2020, citation redacted for review]. The F2F and UDGears projects were offered in back-to-back academic years, and the course enrollment and student demographics were similar across both study groups. However, there were some curricular differences between the UDGears and F2F projects that may confound the findings of our retrospective evaluation. In particular, students were expected to develop more sophisticated design plans and prototypes for the UDGears project than the F2F version, which culminated in a less refined prototype constructed from light duty materials. Given the successful student outcomes from the UDGears project, our institution is choosing to continue with this curriculum, which was designed specifically for online instruction, as courses migrate back to a F2F format.

In conclusion, our team has demonstrated that an open-ended, hands-on engineering design curriculum can be implemented in FYE engineering courses, even in an online setting, without adverse effects to student learning outcomes. The UDGears curriculum leveraged on-campus manufacturing resources to allow students to remotely fabricate their prototypes, which were then delivered to them for assembly and testing. This model may be useful not only in the event of an unplanned transition to online learning – as was the case with the COVID-19 pandemic – but also as institutions look to efficiently deliver hands-on learning experiences at scale in large-enrollment courses.

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