Proceedings of the ASME 2018 International Design Engineering Technical Conferences &
Computers and Information in Engineering Conference
IDETC/CIE 2018
August 26-29, 2018, Quebec City, Canada

DETC2018-85769

TOYING WITH DESIGN: EXPERIENCING DESIGN FOR RAPID PROTOTYPING USING MINI-FABRICATION EXERCISES

Siddharth Banerjee[*], **Caleb Carithers**[*], **Aniket Chavan**[*]
School of Mechanical Engineering
Purdue University
West Lafayette, Indiana 47907

Devarajan Ramanujan
Department of Engineering
Aarhus University
Aarhus C, Denmark 8000

Karthik Ramani[†]
School of Mechanical Engineering
Purdue University
West Lafayette, Indiana 47907

ABSTRACT

This study explores the use of mini-fabrication exercises for helping students learn design for rapid prototyping in computer-aided design and prototyping courses in engineering curricula. To this end, we conducted mini-fabrication exercises in ME444—an undergraduate course at Purdue University. The exercises provide hands-on exposure to design for rapid prototyping principles using simplified design problems. We developed two mini-fabrication exercises in ME444; (i) gear pair design & box design using laser cutting, and (ii) toy catapult design using stereolithography printing. These exercises were tested in a classroom-setting with 51 undergraduate students. Results show the mini-fabrication exercises facilitated students' learning of geometric dimensioning & tolerancing, part sizing, and material properties in laser cutting and stereolithography printing.

1 INTRODUCTION

Rapid prototyping technologies such as additive manufacturing (AM) and laser fabrication have been rapidly adopted by a wide range of engineering companies for concept and final part production [1,2]. Educating students on the use of such technologies has therefore become a strong focus of undergraduate engineering programs. A National Science Foundation (NSF) workshop on education for AM [3] identified the need for developing skills in (i) understanding process-material relationships in AM, (ii) engineering fundamentals with an emphasis on materials science and manufacturing, (iii) design practices and tools that can utilize the freedom enabled by AM, (iv) professional problem solving and critical thinking, and (v) cross-functional teaming and ideation techniques. Undergraduate courses that integrate rapid prototyping with the product design process present a platform for developing such skills in engineering students. However, previous studies have reported that students tend to rush to fabrication without accounting for design flaws or performing model checks [4]. They also ignore considerations for support structures and expect AM parts to have similar endurance to machined parts [5], and find it difficult to learn from mistakes made

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[*] Equally contributing authors
[†] Address all correspondence to this author, ramani@purdue.edu

as they seldom reflect on their errors [6]. Learning aids such as worksheets [5] and expert-supervision during fabrication have been successful in remedying some of these concerns. However, such aids are often used as cautionary tools and do not allow students to learn by reflecting on their mistakes.

In this paper, we discuss the use of mini-fabrication exercises as a means for facilitating students' learning of design for rapid prototyping in undergraduate computer-aided design and prototyping courses. The goal of these exercises is to promote students' exploration of design for manufacturing concepts through simplified design and fabrication tasks. Specifically, we developed two mini-fabrication exercises on design for stereolithograpy 3D printing (SLA) and design for laser cutting (LC). The following sections describe the structure of the two mini-fabrication exercises and detail results from piloting them in ME444[1]—a toy design course at Purdue University.

2 RELATED WORK

2.1 PHYSICAL PROTOTYPING AND RAPID PROTOTYPING IN DESIGN EDUCATION

Physical prototyping helps students refine their mental models about their designs and can improve its functionality [7, 8]. Creating multiple physical prototypes in early design has shown to benefit the quality of the final design [9]. Studies have also shown physical prototyping can reduce design fixation [10], expose design issues not visible in virtual prototyping or sketching [11], improve the aesthetic and functional quality of the final design [12], and help validate design features from a systems perspective [13].

Given such advantages, there has been a focus on increasing physical prototyping in design education through the use of rapid prototyping technologies such as AM and LC. By allowing students to rapidly explore geometric forms and material properties while creating physical artifacts, rapid prototyping can serve as a medium for learning design through making [14]. The ability of AM, LC, and other forms of rapid prototyping to ease the barrier to fabrication, lower fabrication time, and fabricate complex geometric forms have made them especially useful in undergraduate engineering curricula. As a result, rapid prototyping has been integrated into undergraduate engineering curricula through design-focused courses [15,16,17,18,19] and by creating collaborative prototyping spaces [20, 21].

Rapid prototyping technologies such as AM and LC benefit design education by affording rapid iteration and mistake-making in early design. Supporting exploration and failure in early design can improve the efficiency and success of the product design process [22]. Other advantages of using rapid prototyping in design education, include (i) complementing design theory with real product development, (ii) facilitating design decision-making and functional verification, (iii) bringing students closer to new technologies being used in industry, and (iv) exposing students to real design challenges [23].

2.2 DESIGN FOR RAPID PROTOTYPING

2.2.1 DESIGN FOR AM AM improves design freedom and reduces the need to understand design for manufacturing limitations of conventional manufacturing processes [24]. However, AM requires students to develop a new understanding of relationships between geometry, material properties, tolerancing, and other process-specific limitations [25].

Previous research has developed checklists, rule-based catalogs, and worksheets for integrating design for AM (DfAM) considerations into the design process [5, 26]. Such tools usually provide broad guidelines and span across multiple AM techniques. For example, Booth et al. [5] develop a worksheet that scores designs on complexity, functionality, material removal, unsupported features, thin features, stress concentration, tolerances, and geometric exactness. This score is used to estimate the success of the design and recommend fabrication methods. Similarly, Perez et al. [27] extract a set of 23 design principles for AM using crowd-sourced design data from Thingiverse[2]. Such tools provide limited opportunities for learning as the developed principles cannot always be contextualized to a specific design case. Furthermore, the primary focus of such tools is on qualifying a design based on identified best practices rather than facilitating inquiry and reflection on design decisions.

There has also been a focus on aiding DfAM by detailed characterization of AM processes. Gibson et al. [28] discuss elastomeric properties of a living hinge design and experimental results from mechanical testing with results from finite element analysis. Seepersad et al. [29] created benchmark parts from Nylon 12 powder to explore feature resolution, font resolution, and the clearance between moving mechanical parts in selective laser sintering. Miesel & Williams [30] formulate design for manufacturing considerations for multi-material PolyJet 3D printing by experimental testing. Such publications present useful guidelines for designers using similar AM materials and processes. However, their focus is not on facilitating student learning. Doing so, requires integration of learning-focused approaches into DfAM instruction [16].

2.2.2 DESIGN FOR LC Designing for LC is challenging as most computer-aided design (CAD) tools do not explicitly support this process. Sketches required for LC can be generated in CAD programs by projecting 3D models onto a plane. However, CAD programs do not take into account cutting resolution, LASER kerf, taper in cuts, or production of microfissures due to heat affected zones [31]. Therefore, in many cases, designers

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[1] https://engineering.purdue.edu/toydesign

[2] www.thingiverse.com

Table 1: Year of use, resolution, and material properties for 3D printers used in ME444.

	3D Systems SLA 250/30 [34]	Stratasys Mojo 3D Printer [35]	EnvisionTEC Xtreme 3SP SLA 3D Printer [36]
Year of use in ME444	–2015	2015–2016	2016–
3D Printer resolution	0.0025 inch	0.007 inch	0.002 inch
Material	SL5170 resin	P430 ABS plus	Photopolymer OP 13/E Model
Flexural strength	80–85 MPa	96–120 MPa	106 MPa

need to be independently aware of these considerations when designing for LC [32]. Although our literature search yielded publications that describe parameter selection for specific LC processes [33], we did not find papers that formulate design for LC (DfLC) guidelines by studying commonly occuring mistakes.

3 MOTIVATION & RESEARCH QUESTIONS

Our research was motivated from observing the performance of toys in ME444 over the course of the last ten years. We found most failures in these toys stem from (i) stress-related breakage because of components that are too thin or poorly designed, (ii) excessive friction between moving parts due to improper considerations of tolerances or surface finish, (iii) poor assembly due to badly designed joints or interfaces, and (iv) improper selection of actuators or motors to match the inertial and frictional characteristics of the toy. This led us to question the effectiveness of lecture-based instruction to facilitate learning design for rapid prototyping in courses such as ME444. Additionally, the quality of parts capable of being produced in ME444 has been steadily rising (see Tbl. 1). Even with access to improved printers, we noticed that failures in toys did not significantly reduce. This led us to hypothesize that students' approach to design for rapid prototyping, rather than the limitations of the fabrication method, significantly contributed to the observed failures.

In this paper, we explore the use of mini-fabrication exercises as means for addressing the aforementioned gaps. These exercises provide hands-on exposure to design for rapid prototyping principles early in the design process. Our research builds on previous work in learning by making [14] and problem-based learning [16] within design for rapid prototyping. We focus on facilitating experiential learning by developing mini-fabrication exercises that afford exploration, mistake-making, and reflection. Specifically, we discuss mini-fabrication exercises in LC & SLA and the results from a survey-based study that explored the following research questions.

- Is there a need for mini-fabrication exercises in undergraduate computer-aided design and prototyping courses such as ME444?
- Are there any positive learning outcomes due to the introduction of mini-fabrication exercises?
- What is the influence of the mini-fabrication exercises on students' performance in their final design projects?
- What is the feasibility of continuing the mini-fabrication exercises in ME444 and introducing them in other similar courses?

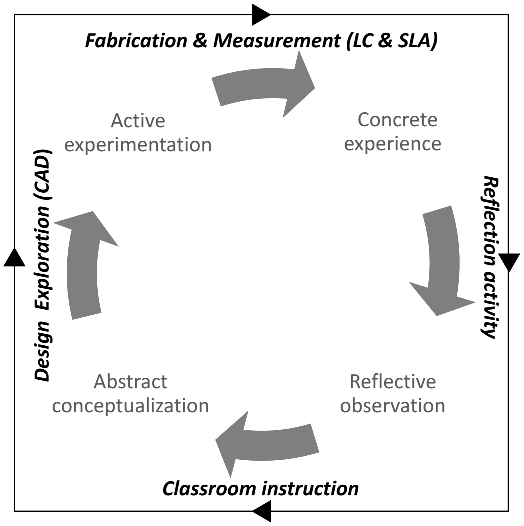


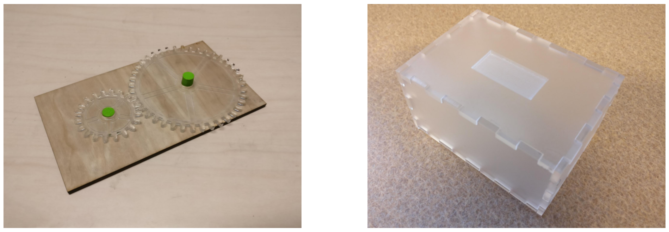
Figure 1: Map of tasks in the mini-fabrication exercise (outer cycle) to Kolb's experiential learning cycle (inner cycle) [37]

4 METHODOLOGY

4.1 MINI-FABRICATION EXERCISES

We developed two mini-fabrication exercises that exposed students to design for rapid prototyping principles in LC & SLA. The exercises consist of 4 tasks that facilitate experiential learning by allowing students to fabricate simplified designs.

1. *Classroom instruction*, where students are encouraged to conceptualize their understanding through presentation and discussion sessions
2. *Exploring solutions for simplified design problems*. In the current paper, the tasks involve designing a box or a pair of gears (for LC) and toy catapult design (for SLA)



(a) An illustrative solution to the gear design problem

(b) An illustrative solution to the box design problem

Figure 2: Design problems in the LC mini-fabrication exercise.

3. *Fabrication and performance measurement of design solutions*. In the current paper this task is limited to parts fabricated using LC & SLA
4. *Reflection activity*, in which students are encouraged to internalize observations from the measurement task

Figure 1 illustrates the mapping between tasks in the mini-fabrication exercise and Kolb's experiential learning cycle [37]. Please note the mapping between a specific task and a stage in Kolb's cycle is not one-to-one. However, stepping through the tasks in the mini-fabrication exercises provides opportunities for experiential learning. Our intention behind developing this framework is two fold. Firstly, experiential learning facilitates learning through mistake-making [38]. Learning generated from failures in early design improves the success of the product design process [22]. Secondly, experiential learning encourages students to discover causal relationships between design choices and part performance. Identifying and conceptualizing such relationships can help students' performance in design projects.

4.1.1 MINI-FABRICATION: LASER CUTTING

The first mini-fabrication exercise exposed students to LC, its potential use for their final toy design project, and LC-specific limitations. The exercise consisted of four tasks (see Fig. 1) that facilitated experiential learning in the context of DfLC.

We started the exercise with classroom instruction as several students had no previous exposure to LC. We explained the operating principles of LC and the use of PTC CREO 2.0 & AutoCAD 2016 software to create drawings for LC. We also discussed how to set parameters in the LC software[3] for creating engravings and through cuts. In addition to these presentations, we distributed sample laser-cut parts along with their design drawings. Students measured part dimensions using a pair of Vernier calipers and compared them to corresponding design dimensions. The goal of this activity was to help students observe real-world implications of setting different tolerances, cut depths, and geometry. These parts also helped students realize the need to account for laser beam thickness while designing for LC.

In the design exploration and the fabrication & measurement tasks, students could choose one of two design problems.

- Gear design problem (individual): Students designed a pair of spur gears with different radii, given a center distance of 3 inches (see Fig. 2(a)). We asked students to design the gears such that they mesh and rotate smoothly.
- Box design problem (group-based): Students (in groups of 2) designed a cuboidal box (3.5×2.5×2 inch) with 6 interlocking faces. We asked students to design the box such that it would form a stable structure without using adhesives (see Fig. 2(b)).

In the gear design problem, students were free to choose different gear radii and tooth profiles. In the box design problem, students could choose different profiles for interlocks. Furthermore, to allow learning through mistake-making, the task was graded on completion as opposed to design performance. Students were given one week to design the parts and create drawing files to be laser cut. They could seek input from the course teaching assistants during the design process. The LC was performed on our in-house LASER cutter [4].

Students explored the real-world implications of their design choices by fabricating the gears and measuring the dimensions of the resulting parts. Please note, the course teaching assistants operated the laser cutter as most students were not certified to use it. Post-fabrication, students verified their design decisions by measuring the differences between the design dimensions and the actual dimensions of the fabricated part. The expected learning outcomes were for students to (i) realize the importance of considering laser beam thickness in their design, and (ii) understand dimensioning for different types of fit. The gear design problem required designing for a sliding fit between the gears and the center shafts, while the box design problem required a transition fit for the box to remain stable without the use of adhesives.

In the reflection task, we provided students with a questionnaire that asked them about (i) deviations between the designed and fabricated dimensions, (ii) reasons why the deviations were present/absent, (iii) learning achieved in the exercise, and (iv) design changes they would make if they used LC again. They were also able to discuss their findings with the teaching assistants and compare them to concepts discussed in classroom instruction.

4.1.2 MINI-FABRICATION: STEREOLITHOGRAPHY 3D PRINTING

The second mini-fabrication exercise exposed students to design considerations for the SLA process and helped them understand limitations of SLA in regards to their final toy design project. This SLA mini-fabrication exercise also consisted of the four tasks illustrated in Fig. 1.

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[3] https://fslaser.com/RetinaEngrave

[4] https://fslaser.com/Product/Pro2416

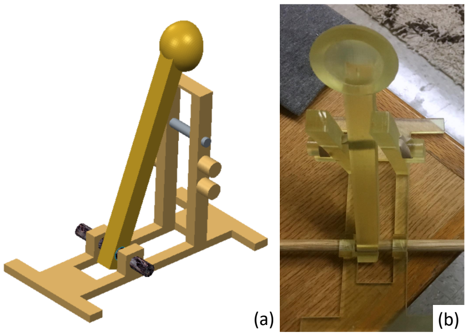

Figure 3: Catapult designed by a student team in the SLA mini-fabrication task; (a) CAD model, (b) fabricated catapult.

First, we provided students with an overview of SLA and specifications for the SLA printer they would use. We also invited the manager of the 3D Printing (3DP) facility to discuss design considerations for creating various types of SLA features. This presentation highlighted design of supported and unsupported walls, overhangs, embossed and engraved features, relief holes, and dimensioning schemes for different types of fits. We also showed students toys from previous student projects and discussed design for SLA principles that were not considered in these toys.

In the design exploration task, students worked in groups of 3 or 4 and designed a rubber band powered toy catapult capable of launching a steel ball weighing 2.06 grams (see Fig. 3). Each team could only use a total of 8.0 $inch^3$ (or less) of SLA material and the size of a single part was restricted to 10 inches or less. These constraints mimicked those present in the final toy design project (Section 3.2). We imposed no other restrictions on the design of the catapult. To motivate the design process, we told students they would participate in a competition to test which catapult could launch the ball the furthest. Students were explicitly told their grade on this assignment was based on completion and not on final performance. Each team had one week to model their parts using a CAD program. Please note, students were free to seek input from the course teaching assistants and the 3DP facility manager during the design process.

The parts were fabricated on an EnvisionTEC printer [36] by the 3DP facility manager. Students were encouraged to discuss the fabrication process with him and observe the printing and post-processing of their parts. Post-fabrication, students analyzed parts for deviations from design dimensions, shape distortions, surface finish, and structural rigidity. The expected learning outcomes were for students to (i) realize the limitations of SLA, (ii) explore means for reducing support structures, (iii) understand dimensioning for different types of fits, and (iv) realize the correlation between print orientation and shape distortion.

Similar to the LC mini-fabrication exercise, students reflected on implications of their design decisions after the catapults were built. Additionally, students participated in the ball launching competition and observed the comparative influence of design choices on the performance of the catapult. After the competition, we asked students about, (i) types of failures in the catapult, (ii) their understanding of observed failures, (iii) learned achieved in the exercise, and (iv) precautions they would take while using SLA in the final toy design project based on this experience.

4.2 FINAL TOY DESIGN PROJECT

Students worked on their final toy design project from Week 4 through Week 16 in groups of 3 or 4. Groups developed proposals for their toy for the first three weeks. After proposal approval, groups had another four weeks to complete designing the toy using a computer-aided design software. All groups were required to use SLA fabrication on their final project. Each group could use up to 15 $inch^3$ of SLA material for their toys. The maximum linear dimension of a part was restricted to 10 inches due to the size of the build plate. Each group also had a $60 budget to purchase additional parts (e.g. motors, electronics, and other materials). A portion of this budget could be used for purchasing materials for LC or additional material for 3DP. However, any additional 3DP was done by the groups themselves using other facilities available on campus. Groups received the 3D printed parts by Week 15 and had until the the end of Week 16 to assemble and demonstrate their toys. Figure 4 illustrates the types of toys produced in the final design project.

4.3 SURVEYS

We surveyed students in ME444 to understand the usefulness of two mini-fabrication exercises. Please note, completion of these surveys was voluntary and did not contribute to course grade. Figure 5 illustrates the timeline of the mini-fabrication exercises, surveys, and the final toy design project in ME444. Interested readers can download the surveys and other supporting material from the following link: https://goo.gl/9cagpd.

4.3.1 DEMOGRAPHICS SURVEY

The demographics survey (demo. survey in Fig. 5) was distributed to the students in Week 2 prior to the mini-fabrication exercises. This survey was aimed at understanding students' academic background, their prior experience with LC & SLA, and their understanding of geometric dimensioning and concepts relevant to LC & SLA.

4.3.2 LC & SLA SURVEYS

During the reflection task in each mini-fabrication exercise, we asked students to complete questionnaire-based surveys on the learning obtained from the respective exercises. In the LC survey, students reported observed deviations between the fabricated parts and the designed parts and described their understanding of what caused them.

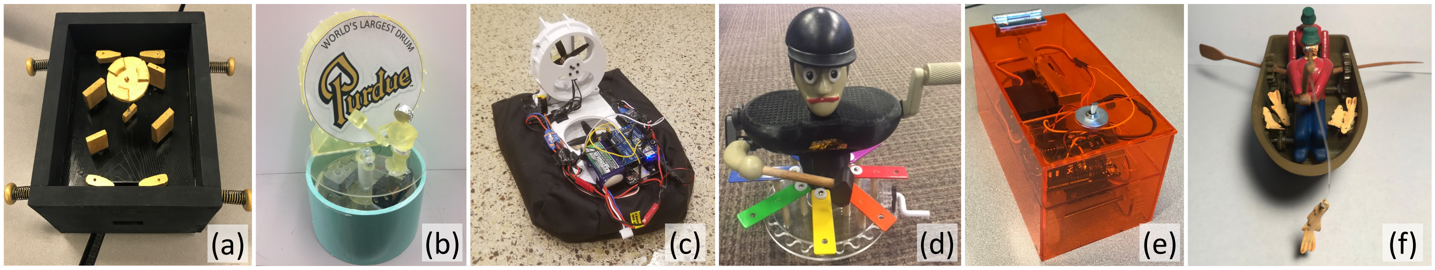

Figure 4: Sample toys fabricated by groups in ME444: (a) two person pinball game, (b) Purdue University's big bass drum, (c) radio frequency controlled hovercraft, (d) Purdue Pete Xylophone, (e) do almost nothing box, and (f) fishing boat.

	W01	W02	W03	W04	W05	W06	W07	W08	W09	W10	W11	W12	W13	W14	W15	W16
LC mini-fabrication exercise			LC mini-fab													
SLA mini-fabrication exercise					SLA mini-fab											
Surveys		Demo. survey		LC survey					SLA survey							Final Survey
Final Design Project				Proposals				CAD modeling				Fabrication			Assembly	

Figure 5: Timeline of mini-fabrication exercises, surveys, and the final project in ME444.

We also asked students if the exercise had made them aware of DfLC considerations that may be useful for the final toy design project. In the SLA survey, students reported the types of failures that they experienced during assembly and operation of the catapult. We asked students to summarize their understanding of what caused these failures and how they would modify their designs to avoid them.

4.3.3 FINAL SURVEY

After students demonstrated their toy prototypes (Week 16), we surveyed each team to understand the impact of mini-fabrication exercises on their final toy design project. The final survey consisted of two parts, an individual questionnaire and a group-based interview. The questionnaire asked students to evaluate, (i) the need for mini-fabrication exercises in ME444, (ii) if the mini-fabrication exercises help them learn DfAM and DfLC concepts relevant to the final toy design project, and (iii) whether the mini-fabrication exercises helped in reducing specific failures (e.g. strength-related, tolerance-related, and assembly-related) in the final toy. After completing the questionnaire, we conducted a semi-structured interview with each group where we discussed learning outcomes from the mini-fabrication exercise. We used a semi-structured interview process as it gave groups the freedom to express their views and because we would not have been able to conduct follow up interviews with them [39]. The interviewer discussed the following topics with each group, (i) satisfaction with the performance of their final toy, (ii) kinds of failures they experienced in the final toy, (iii) reflections on the causes of these failures, (iv) reflections on the usefulness of mini-fabrication exercises with regards to the final toy design project, and (v) suggestions for modifying the mini-fabrication exercises.

5 RESULTS

5.1 OBSERVATIONS FROM THE MINI-FABRICATION EXERCISES

In the LC mini-fabrication task, 12 students (6 two-member groups) opted for the box design problem and the remaining 39 students opted for the gear design problem. We found all students who designed boxes added their own engraving features and customized interlocking features. Furthermore, 2 teams designed boxes so they could be turned into lanterns and candle holders. Among the students who designed gears, only 6 students used CAD-based gear design software. The rest of the students designed their own gear teeth. We also observed students were excited to participate in the LC mini-fabrication task as a majority did not have any prior experience in LC (see Fig.6).

Students worked in teams of 3-4 members in the SLA mini-fabrication task 9 four-member teams and 5 three-member teams). Among the 14 teams, one team designed a Balista type catapult, while all other teams designed Mangonel type catapults. We found that students did not account for the brittleness of the SLA material in their design and therefore did not incorporate stoppers or other shock absorbing features to cushion the impact of the catapult's launcher arm on its frame. After assembling

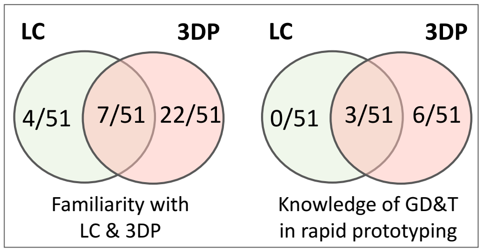

Figure 6: Students' familiarity with LC & 3DP and their knowledge of GD&T concepts in rapid prototyping.

the catapults two teams wrapped a piece of sponge on the catapult arm while others shortened the arm's swing by stopping it earlier than the designed projectile release point. We found the SLA mini-fabrication exercise surprised students as they did not anticipate the surface finish and structural properties of parts produced by the EnvisonTEC printer. Consequently, several teams had over-designed structural parts. We did not find any relationship between team size and performance on the task.

5.2 RESULTS FROM THE SURVEYS

5.2.1 DEMOGRAPHICS SURVEY We received 51 responses for the demographics survey from the total class strength of 51 (response rate = 100%). From them, 7 students were in their final semester and 44 students were 1-2 semesters away from completion of their program. A significant majority of students were in the mechanical engineering program (45/51), 3 students were in the biomechanical engineering program, and 3 students were in the interdisciplinary engineering program. From the 51 respondents, 47 students were male and 4 were female.

We asked students about their understanding of geometric dimensioning & tolerancing (GD&T) and analyzed their responses based on whether they discussed the following concepts (i) degree of accuracy and precision needed while defining a part feature, (ii) nominal geometry & allowable variation in part features, and (iii) allowable variation in form and sizing between features. Results show 48/51 students discussed at least one of these three concepts and 4/51 mentioned all three concepts. We also asked students about their previous experience with LC & 3DP and GD&T in rapid prototyping (see Fig. 6).

5.2.2 LC SURVEY We received 44 responses for the LC survey (response rate = 86.27%). In the LC mini-fabrication exercise, 11/33 students who opted for the gear design problem and 1/11 students who opted for the box design problem reported deviation in part dimensions beyond the specified design tolerance. We also found 8/33 students reported that the gears did not mesh and 3/11 students reported the fabricated boxes could not be assembled. We found predominant reasons for failure were (i) unexpected burrs on cut edges, (ii) larger than expected dimensions, (iii) undersized dimensions, and (iv) poorly designed teeth and joints. There was no correlation between students' familiarity with LC and the likelihood of failure on the task (*Two-tailed Fisher's exact test*, $p = 0.4082$)

We also analyzed students' reflections and found 10/11 students in the box design task and 26/33 students in the gear design task were able to correctly identify the causes of failure or successes in their designs. Student's ability to explain the cause for the observed design performance did not significantly depend on their prior knowledge of GD&T concepts (*Two-tailed Fisher's exact test*, $p = 0.4609$). In the LC survey, 6/11 students in the box design task and 21/33 students in the gear design task mentioned that they identified important takeaways for the final toy design project. Table 2 summarizes students' comments on measures they would take while using LC in the final toy design project.

5.2.3 SLA SURVEY We received 31 responses for the SLA survey (response rate = 60.78%). Results from the SLA survey show, 24/31 students reported some kind of failure in the fabricated catapults. We found there was no significant effect of students' reported familiarity with 3DP on the likelihood of committing failures reported in the catapult (*Two-tailed Fisher's exact test*, $p = 0.4130$). The reasons given for failure, included (i) improper tolerancing/clearance, (ii) improper part sizing, and (iii) not considering SLA material properties during design. When compared to students who reported some previous knowledge in GD&T concepts in 3DP, students who reported no previous knowledge were more likely to commit failures due to improper clearances, (*One-tailed Fisher's exact test*, $p = 0.0303$), and improper design sizing (*One-tailed Fisher's exact test*, $p = 0.0475$). However, there was no significant difference between the groups for failures due to lack of consideration of material properties (*Two-tailed Fisher's exact test*, $p > 0.99$). Analysis of student's reflections in the SLA mini-fabrication task showed 27/31 students were able explain why their catapult designs were successful or failed. We found students' ability to explain the cause for the observed design performance did not significantly depend on their prior knowledge in GD&T concepts (*Two-tailed Fisher's exact test*, $p = 0.9871$). The SLA survey also showed 15/31 students were able to identify important takeaways for the final toy design project. Table 3 summarizes students comments on measures they would take while using SLA in their final project.

5.2.4 FINAL SURVEY We received 49 responses for the questionnaire in the final survey (response rate = 96.07%), while all 51 students participated in the group-based interview. In the questionnaire, students reported on a Likert scale (1= strongly disagree, 5=strongly agree) the mini-fabrication exercises helped them learn concepts in tolerancing ($\mu = 4.30$, $\sigma^2 = 0.34$) and structural design ($\mu = 4.19$, $\sigma^2 = 0.55$) that were

Table 2: Classification of students' reflections from LC mini-fabrication task. The table lists number of reflections (N) and illustrative examples for each category.

Specify tolerances based on experience in LC mini-fabrication task ($N = 34$)	Increase the number of design iterations/time ($N = 10$)	Use alternate manufacturing methods ($N = 3$)	More oversight of fabrication process ($N = 2$)
"For my final design, I will adjust the tolerances to ensure that all the mated parts fit as expected whether it's a clearance or an interference."	*"I didn't try making the teeth larger and regret not doing that. I will take more time to consider the different design options for the final toy design project."*	*"For parts that I am unsure of performance, I will first create them in a cheaper/faster physical medium to make sure the design behaves as expected."*	*"I will always be present when my parts are being fabricated, in order to ensure the process goes smoothly."*
"I will be sure to include the width of the laser when dimensioning the parts to be cut with the laser."	*"I will take more time to understand how the final product will be assembled when compared to the design."*	*"If given a certain amount of money (budget), I will utilize it to choose a technique which can provide better accuracy in dimensions."*	

Table 3: Classification of students' reflections from SLA mini-fabrication task The table lists number of reflections (N) and illustrative examples for each category.

Specify tolerances and size parts based on experience in SLA mini-fabrication task ($N = 21$)	Design parts based on material properties observed in SLA mini-fabrication task ($N = 6$)	Account for print orientation while designing parts ($N = 2$)	Assemble virtual prototype in CAD software ($N = 4$)
"Allowing better design for clearances/tolerances to provide adjustable components along with focusing on the motions/goals is required."	*"We will design parts to minimize warpable geometries and use such parts in low force or low cycle applications."*	*"I will be sure to know exactly what orientation the part will print in...our arm was printed in an odd orientation which may become relevant when we begin printing for the final project."*	*"Measure twice, print once. Before submitting the final design, I will make sure to instance exactly how pieces will fit together."*

necessary for the final design project. Students' responses to whether the mini-fabrication exercises helped them test out ideas of the final toy design project were slightly positive ($\mu = 3.78$, $\sigma^2 = 1.15$). Students supported continuing the LC ($\mu = 4.39$, $\sigma^2 = 0.64$) and SLA ($\mu = 4.48$, $\sigma^2 = 0.52$) mini-fabrication exercises in future ME444 classes. Students were against replacing the LC ($\mu = 2.11$, $\sigma^2 = 1.6$) and SLA ($\mu = 2.00$, $\sigma^2 = 1.20$) mini-fabrication exercises with equivalent lectures on DfLC and DfAM. We also found there was some support for including additional design problems in LC ($\mu = 3.02$, $\sigma^2 = 1.17$) and SLA ($\mu = 3.93$, $\sigma^2 = 0.86$) mini-fabrication exercises.

All 14 teams participated in the group interview portion of the final survey. We categorized teams learning of concepts useful for their final projects and specific changes they made to their toys based on their experience in the mini-fabrication tasks (see Tbl. 4). We found the mini-fabrication exercises were the most useful in helping students learn about tolerancing and physical properties (e.g. friction, strength). Students reported the exercises were not useful in learning about CAD modeling and mechanism design as the design problems were simpler than their final toys. We found teams reported making specific changes to their designs in all concepts except CAD modeling.

We also categorized causes for failure in the final toy design project by relating them to concepts identified from the group interview. For each toy, failures were identified based on the type of failure reported by the student team in the final survey and the group interviews (see supporting material linked in Section 4.3 for further details). The authors also inspected the final toy designs produced by the teams to verify functional failures reported. It was possible for a single toy to consist of more than one failure mode. Figure 7 compares failure causes reported by students in Fall 2017 (semester in which the mini-fabrication exer-

Table 4: Responses from group interviews in the final survey. The LC exercise & SLA exercise columns count teams that reported learning specific concepts useful for their final toy design project. The last column counts teams that reported making a change to the final toy based on their experience in the mini-fabrication exercises.

Concepts	LC exercise	SLA exercise	Changes to final toy
Mechanism design	1	1	1
Tolerances	3	4	7
Physical properties	1	8	3
Printing errors	1	0	2
Sizing	0	2	2
CAD modeling	0	0	0
Do not recollect	0	0	3

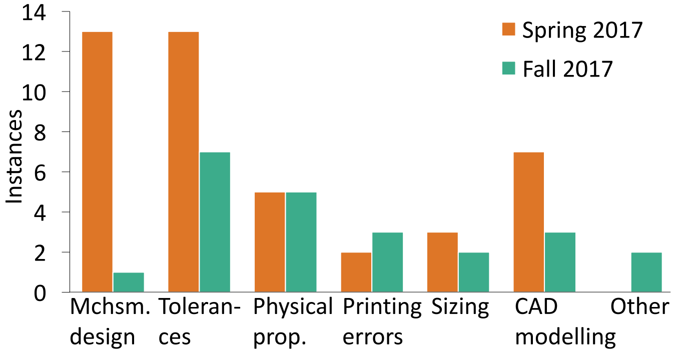

Figure 7: Classification of failure causes in final toys for Spring 2017 (total teams = 13) and Fall 2017 (total teams = 14). Please note, mini-fabrication exercises were conducted in Fall 2017.

cises were conducted) and the previous semester (Spring 2017). Results show both (i) total number of failures, and (ii) failure related to mechanism design, tolerances, sizing, and CAD modeling decreased in Fall 2017. The largest decreases were in mechanism design and tolerance-related failures. The predominant reasons for failure in Fall 2017 were incorrect tolerancing of holes that interfaced with store-bought pins (4 teams) and excessive friction due to improper design of SLA-fabricated gears (4 teams).

6 DISCUSSIONS

In this section, we answer the research questions outlined earlier based on the results from the mini-fabrication exercises and the surveys.

- **Is there a need for mini-fabrication exercises in undergraduate computer-aided design and prototyping courses such as ME444**

We found a majority of students in ME444 had some understanding of GD&T concepts. However, only 7 students had previous experience with both LC and 3DP prior to the class. Among them, only 3 students reported having an understanding of GD&T considerations in rapid prototyping. We also found that previous knowledge of GD&T concepts did not significantly decrease students' likelihood of material properties related failures (e.g. edge burrs, fracture, excessive friction) in LC and SLA. Such knowledge gaps, coupled with systems-related challenges in creating mechatronic toys, caused student teams to create non-functioning toys in their final toy design projects. In spite of lecture-based instruction on DfAM & DfLC, and improving capabilities of SLA fabrication, our observations show failures in the final toy design project did not significantly decrease in past years. These findings point to the need for hands-on instruction methods that (i) expose students to SLA and LC before the final project, and (ii) facilitate experiential learning of DfAM and DfLC principles. Other previous studies [4,5,6] also detail that students have a limited understanding of DfAM principles. This lends further support for increasing instruction on DfAM and DfLC concepts in other undergraduate computer-aided design and prototyping courses.

- **Are there any positive learning outcomes due to the introduction of mini-fabrication exercises?**

Results from the final survey show the mini-fabrication exercises helped students learn concepts in tolerancing and material's physical properties that were necessary for the final design project. The hands-on nature of the mini-fabrication exercises seems to foster students' experiential learning. We also found students' ability to identify takeaways from the mini-fabrication exercises was dependant on their degree of failure. Students' learning was better when the designs failed partially (e.g. gears did not mesh smoothly, catapult arm cracked after a few ball launches), rather than completely (e.g. gears did not mesh, the box did not assemble). This finding suggests retaining the focus of mini-fabrication exercises to simplified design problems. However, the problems should involve complex motion and assembly with non-rapid prototyped parts to improve students' learning in concepts such as mechanism design, CAD modeling, and assembly tolerancing.

- **What is the influence of the mini-fabrication exercises on performance in their final design projects?**

We found total number of failures in the final toy design project decreased in Fall 2017 (semester in which the mini-fabrication exercises were conducted) compared to the previous semester (Spring 2017). The decreases seen were in mechanism-design, tolerance, sizing, and CAD modeling-related failures. While these results are promising, more comparative studies are required to verify this finding. Students' responses show the mini-fabrication exercises facilitated learning useful for the final toy design project. However, the exercises were only marginally helpful for testing out ideas for the final design project. Data from the group interviews also shows students felt the design problems in the mini-fabrication exercises were disconnected from the final toy design project. Reducing this disconnect may help improve the students' performance in the final toy.

- **What is the feasibility of continuing the mini-fabrication exercises in ME444 and introducing them in other similar courses?**

Students' feedback shows there was support for continuing the LC and SLA mini-fabrication exercises in ME444. Students were also against replacing these exercises with equivalent lectures. Our discussion with the course instructor pointed to the need for managing course load due to the mini-fabrication exercises by improving its integration with the final toy design project. Even so, the course instructor felt the exercises added value to the course and was in favor of continuing them in the coming semesters. When comparing the changes in course content with the previous semester, the inclusion of the mini-fabrication exercises did not result in significant changes to lecture content. The number of quizzes in the course was reduced to 5 from 6 and the the total weighting of course quizzes was reduced by 7% to accommodate the exercises. This points to the feasibility of introducing similar mini-fabrication exercises in other similar courses. However, future work is required to identify approaches for successfully adapting mini-fabrication exercises to other computer-aided design and prototyping courses in undergraduate engineering curricula.

7 LIMITATIONS

Our study did not compare mini-fabrication exercises against other methods of instruction. Furthermore, as the current study was exploratory, we did not analyze students' design or cognitive processes during the mini-fabrication exercises or the final toy design project. Such studies are needed to fully understand the benefits and limitations of the mini-fabrication exercises. Students in ME444 did not directly operate the SLA printer or the laser cutter due to lack of necessary qualifications. Increasing their ownership in fabrication tasks (by using other lower fidelity machines) could improve learning outcomes.

8 CONCLUSIONS & FUTURE WORK

In this work, we developed mini-fabrication exercises to help students learn design for rapid prototyping in LC and SLA. These exercises facilitated experiential learning of DfAM and DfMLC principles by exposing students to simplified design problems while they worked on a larger design project. The mini-fabrication exercises consist of four tasks: classroom instruction, design exploration, fabrication & measurement, and reflection. We tested the mini-fabrication exercises with students in ME444–an undergraduate level toy design and prototyping course at Purdue University. Our study shows (i) there is a need for hands-on instruction of DfAM and DfMLC principles in undergraduate computer-aided design and prototyping courses such as ME444, (ii) mini-fabrication exercises helped students learn design for rapid prototyping principles that were useful in their final design projects, and (iii) students were in favor of continuing the mini-fabrication exercises and preferred it over lecture-based instruction of DfAM and DfLC concepts.

Limitations discovered in our study point to future work that could improve the mini-fabrication exercises. We found a need for the design problems in the mini-fabrication tasks to be more relevant to the final toy design project. We also found a need for increasing the focus on designing moving parts and interfacing with non rapid-prototyped parts. Our future studies will explore comparing the developed mini-fabrication exercises with alternate instruction approaches.

ACKNOWLEDGMENT

Our thanks to the ME444 course instructor Dr. Min Liu and Mike Sherwood, the manager of the 3DP facility for supporting the study. This work was partly supported by the National Science Foundation (IIS #1422341 and IIP #1632154), the Donald W. Feddersen Chair Professorship from the School of Mechanical Engineering at Purdue University, and the Department of Engineering at Aarhus University. Any opinions, findings, or recommendations presented are those of the author(s) and do not necessarily reflect the views of the funding agency.

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