TANGIBLE SKETCHING WITH 3D PRINTING

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1. INTRODUCTION THE LAYOUT OF THE PAPER

Throughout history, there is a noted reciprocity between tools and artifacts. Technology has become a tool for both the exploration and production of and its means and self-expression. Unlike earlier industrial production and market models, it is now feasible that we, the designer, engineer, manufacturer, and consumer can become collaborators in the creation of the narrative and the experiences it ensues if we so choose.

Technology has become an integral part of the graduate "studio" experience and has advanced the dynamic interaction of students in understanding, discussing and analyzing design concepts. A collaborative project between an industrial design graduate studio and two industry leaders, one in CAD software and the other one in 3D printing, is described in this paper and used as a model workflow. This collaboration highlights the high value of tangible assets (3D prints) when evaluating design concepts. It is a wonderful thing to watch students teaching students, faculty, and industry on technology processes known or discovered (printing, software) and, in turn, taking ownership of both their processes and their designs.

The result is a design process that provides flexibility and integration of technologies as ways to expand the exploration of potential solutions in both breadth and depth. This workflow is a novel example of how technology benefits efficiency and relevance of design education and practice.

2. UNDERSTANDING WORKFLOWS IN THE STUDIO

The studio environment is a critical component of the design workflow. Setups such as open studios with assigned desks, shared work tables and group meeting areas encourage continuous collaboration and interaction. However, limitations of space limit the integration of fabrication spaces, both traditional (model shops) and digital (additive manufacturing laboratories and making tools available to students is an evident challenge. For digital fabrication laboratories (Fab Labs), it is common for students to send digital files and have them printed or laser cut for a nominal fee. This service is hands off for the student, and the machines are cloistered behind closed doors. People can look in, but the work, set up, and prints are done by a technician. When prints are finished the student is contacted and prints are picked up. There are also additional resource labs throughout the campus with various levels of accessibility. For traditional processes, facilities like these are adequate, but often in the final weeks of the semester all labs are well beyond capacity, and all students are in dire need of their final print.

The education sector is constantly trying to stay up-to-date on "state of the art" technology. However, this begs the question, "what might that be? At one point, we spent much time teaching about technology. We now have the opportunity to teach *using* technology. Currently, 3D printing is not often used as a back and forth iterative "process" but rather considered the "final outcome" of the design solution. Below are two examples of how digital fabrication have been integrated into studio courses (Tables 1 and 2).

Form class
This course focuses on exploration of form and fabrication, as a way of enabling physical interaction between people and objects. *In this case, p*rinting is used as both starting and ending points. Key steps include:

1. **Physical exploration:** Students move quickly from clay sketches to analysis, followed by digital models and preliminary concepts.
2. **Printing:** file sent to Fab Lab for printing
    a. Over the next few days, issues with files, printers, email communication, etc., delay the process and detract from concept refinement.
    b. Print is obtained.
3. **Refinement:** Print (abstract form) is analyzed, and the digital model modified as needed.
    a. Form then goes through a series of making and analytical processes
    b. Additional processes such as CNC, stack lamination, shape exploration, mold/plaster casting, etc., focus on form refinement.
4. **Exploration:** Scanning finalized plaster.
5. **Digital manipulation:** Including scale, shell, inserting components, etc.
6. **Final design:** Final Print obtained (or mold to cast other material (silicon, etc.).

Table 1: Workflow for Form class

Studio class
Project-based course that focuses on problem-solving and follows typical development of new design solutions around key user needs. Although the topics and scope are varied, the majority of design studio courses follow a similar format:

1. **Research**
2. **Concept development**
    a. 2D Ideation
    b. 2D refinement
    c. Rough 3D mockup
    d. CAD model
    e. Final rendering and/or model
    f. Shop model or
    g. Digital File sent to service bureau
3. Over the next few days, issues with files, printers, email communication, etc., delay the process and detract from concept refinement.
4. **Final print is obtained**.
5. **Final Presentation**.

Table 2: Workflow for design-studio class

The two examples above highlight a predominantly linear process. Most of the “design exploration” happens in a physical way, while digital work (CAD and digital fabrication) serve primarily as a translation of ideas into tangible elements. This pattern creates a separation between physical and digital tools, and prevents students from integrating CAD and fabrication into various steps of their design process.

3. 3D PRINTING AS AN EVOLVING TOOL FOR VISUALIZATION AND FABRICATION

Up until recent years, many industrial 3D printers were large, heavy, inaccessible machines gated by a technician in a prototyping lab, off limits to the average user, let alone students. A complex user flow, and notably high prices, made 3D printers present only at the later stages of prototyping or as a high-end physical rendering tool for professional designers and engineers. (Flynt, 2018) Today, several high-profile desktop 3D printing companies have lowered the barriers of entry to 3D printing but arguably not enough progress has been made in establishing 3D printers as rapid prototyping machines aimed at creating fast physical renders of a designer’s ideas.

Only 10 years have passed since desktop 3D printers emerged after the first Fused Deposition Modeling (FDM) patents expired. (3D Printing Industry, 2019, and Patent:US005121329). Today, we begin to see mass adoption of 3D printers as prototyping tools, not necessarily aimed at creating finished parts and components but rather machines capable of expediting the development process of an idea.

Today's 3D printers can be grouped into two main applications:

- 3D Printing for manufacturing end use and functional parts
- 3D Printing for prototyping (rapid prototyping)

3D printing for manufacturing usually encompasses short production runs of complex parts printed in exotic alloys or composites. Applications can be found across different industries, including aerospace, healthcare and automotive.

On the other hand, 3D printing for prototyping places itself throughout the development process of a new product. Regardless of the intended manufacturing method (injection molding, casting, milling, etc.), 3D printing for prototyping allows the user to scope out the physical reality of a model before committing to a final version. The integration of 3D printing earlier on the development process enables the designer to have a much richer and deeper understanding of the problem at hand. Ultimately, we are physical beings who interact physically with our surroundings. When using CAD, we are still only accessing a 2D representation of a 3D object. Even if said object appears to be free floating in the digital sphere, the information that we can derive from it is still limited. (Inc.com, 2018) In several ways, our brains are still abstracting 2D visualizations. With a model, or specifically a 3D printed model, the idea has now established itself in the physical realm and can be interpreted directly by the observer without any need of abstraction. Simply put, the amount of information that we get out of a 3D printed models many times richer. If an image is worth a thousand words, a 3D printed object is worth a thousand images.

However, the benefits of 3D printed prototyping are often overshadowed by similar problems present in 3D printing for manufacturing. High costs, complex industrial 3D printers gated by a technician or unreliable desktop systems often prevent users from achieving a consistent iterative flow with a 3D printer. To truly support rapid prototyping, there needs to be a seamless, reliable and user centered approach. Integrating 3D printing throughout the design cycle means accessing two key benefits. Physically testing out ideas and challenging them to perform in the real world (thus discovering potential flaws or enhancing concepts earlier in the process) and making ideas tangible to create real products, objects or solutions. There is an inherent commitment to an idea as soon as it leaves the screen and starts existing in the physical realm.

4. INTEGRATING 3D PRINTING INTO DESIGN EDUCATION

In order to apply the concepts and methods explained earlier, a multi-year graduate-level course in industrial design was set up to integrate analog (sketching and modelmaking) and digital tools (CAD, 3D printing and 3D scanning). This course is part of Rochester Institute of Technology's graduate industrial design program, which consistently ranks among the U.S. top ten and offers a 2-year, 60 credit Master of Fine Arts (MFA). The curriculum integrates applied research, human centered process and design for meaningful intent. Students are immersed in a methodology that celebrates their diverse cultural and professional backgrounds as they explore current design theory, progressive skill sets and a rich variety of projects, topics and applications. A curricular map of the program (Table 3) provides more detail on how different topics and courses are covered.

Year 1	**Fall**		**Spring**	
	Design Laboratory I	3	Design Laboratory II	3
	Function of Form	3	Form of Function	3
	2D Ideation & Visualization	3	Integrated Design Visualization	3
	Design History Seminar	3	Design Research & Proposals	3
	Technology Studio	3	Elective/Minor	3
		15		**15**

Year 2	**Fall**		**Spring**	
	Thesis: Research & Planning	6	Thesis: Implementation	6
	Graduate Design Studio I	3	Graduate Design Studio II	3
	Art History Elective	3	Elective / Minor	3
	Design Elective	3	Design Elective	3
	Elective / Minor	3	Elective / Minor	3
		15		**15**
	Total Semester Credits: 60			

Table 3: Model curriculum for MFA program In Industrial Design

Throughout the course students were able to move repeatedly from physical to digital models and back as they developed concepts for wearable products. This iterative process allowed for a broad and deep exploration of how technology improves product development, by enhancing methods for design, testing, refinement and fabrication of consumer products. (Smith, et al., 2015) The course was sponsored by Autodesk and Makerbot, leading manufacturers of CAD software and 3D printers, respectively. Their periodical visits, training and interaction with students provided a high level of engagement and resolution to the courses (Figure 1).

Figure 1: Students, faculty and industry sponsors during a critique.

Concept development is a key component in disciplines such as industrial design. Successful design solutions are often the result of continuous testing, refinement and improvement, as potential issues of a given concept are discovered and resolved.

A typical process used in the course involved students creating mockups made out of everyday materials and capturing them digitally via 3D scanning and photogrammetry. The digital models were refined in CAD software and then 3D printed for further testing and refinement. The process was repeated multiple times as students continued refining their concepts. Key tools used in the course were Autodesk Fusion 360, a CAD software with both parametric and T-splines capabilities, as well as Makerbot Replicator FDM 3D printers, as they provided simple and intuitive interaction with consistent results.

The methods used in this course illustrated how to easily and repetitively integrate digital and physical tools for design and fabrication, in order to improve concept development processes. By adopting workflows similar to this, designers and engineers are able to turn initial ideas into final concepts in a more efficient, effective and engaging way.

5. USING TECHNOLOGY TO ENHANCE EXPLORATION AND LEARNING

Students developed design concepts around wearable technology that highlighted this iterative digital and physical process. The design concepts focused on a wide variety of categories, including: navigation, healthcare and wellbeing, relationships, pet care, entertainment, jewelry and toys. The final designs highlighted how analog and 3D printed models were used interchangeably as design concepts were developed.

The main goals of the courses were to:

- Enable understanding of CAD and 3D printing tools as part of the product design process.
- Develop innovative workflows that combine the use of digital and analog models.
- Enable active, meaningful collaboration between industry and academia.

A key focus of these courses was to develop workflows that translate design concepts between digital and physical environments in an innovative and dynamic way. This process differs from current practices where translation tends to be unidirectional (i.e. CAD into 3D print) but difficult to do the reverse and go from a physical model to CAD in an accurate and efficient way. The goal of these courses was to benefit from the industry sponsors' expertise in finding ways for students to develop these iterative processes that refine concepts by jumping between physical and digital models (Figure 2).

Figure 2: Samples of models from one of the students, including clay, foam, 3D printed, and CAD formats.

Another key component for the courses was the setup of 3D printers in the very design studio where the students work. This is significantly different from print service labs where students simply submit their files and then pick up their finished models, removing them from an important realization process. In this case, students were able to manage and print their own designs directly, which made them more aware of details around 3D printing, including best practices for model creation and even troubleshooting and maintenance of the printers. This model was a great way to test high iterative cycles on students with offer full access to 3D printers, who are working on real world projects that need to evolve quickly, have specific constraints and require a solid and reliable platform on which to prototype (Greenhalgh, 2015). This studio setup also alleviated the intimidation of 3D printing and allowed students to embrace it as another tool in their skillset for product development.

6. STUDENT OUTCOMES

As the project progressed, it was evident that students appreciated the flexibility of integrating physical and digital tools and the ability to go back and forth as many times as necessary. Departing from the design brief of developing wearable solutions, students successfully integrated notions of user experience, human factors and technology into their solutions, which covered topics as diverse as medical, exercise, entertainment, navigation and jewelry, to name a few. A few examples of the students' final designs are noted below:

Yueyue (Zoey) Zhang designed a dog leash (Figure 3) that addresses how current designs with a single loop create strain on the wrist and are difficult to hold when a dog pulls away from the owner. Her design process went through dozens of iterations that addressed form, ergonomics and interaction. The final design uses both the hand and wrist to achieve better control while also providing a retractable leash system.

Figure 3: Retractable dog leash by Yueyue (Zoey) Zhang.

Mintesinot Gebre designed a time management watch (Figure 4). This device measures the amount of time spent in a given project and the progress that has been made on it. The user is able to visualize if they are ahead or behind in a project with a central bar display.

Figure 4: Time management watch by Mintesinot Gebre.

Yinan Luan developed an innovative take on a shopping list (Figure 5). As family members notice grocery items that are needed in the home, they put charms that represent such items in a bowl. When someone is ready to go to the grocery store, they place a magnetic bracelet in the bowl, which picks up the charms. As items are being picked at the grocery store, the charms are put away and brought back home to create a new list.

Figure 5: Shopping list charm bracelet by Yinan Luan.

7. IMPACT OF 3D PRINTING IN DESIGN EDUCATION

The method illustrated in this paper has a significant impact in the design process, making it highly flexible and tangible. The proposed workflow allows designers to move back and forth between analog and digital models at any point in their development process, and helps them to look at accessible 3D printing as a natural step in the exploration and refinement of any product. This adoption of technology as part of an iterative process provides students with a toolset for executing their design concepts effectively and easily.

This project has also illustrated that collaboration gathers around availability and hands-on accessibility. The success of this workflow is to have 3D printers as close as possible to where designers work, ideally in their own studio space. This setup allows for direct and continuous access to the technology, making it more integrated with the overall creative process, and often inspiring new directions. This is an improved model for learning and adoption of technology, which moves away from most service-based prototyping labs, where designers submit files digitally and then pick up finished models, removing them from the actual process of 3D printing.

This collaborative project highlights tangible assets (3D Prints) as a critical component when evaluating design concepts. Technology has become an integral part of the graduate “studio” experience and has advanced the dynamic interaction of students in understanding, discussing and analyzing design concepts. Students are teaching students, faculty, and industry on technology processes (printing, software) and developing new methods. This, in turn, has instilled a sense of ownership in their processes and their designs.

8. CONCLUSIONS

Technology is more prevalent today than ever before, and this is a pattern that will continue to grow. Designers are fortunate to be in the middle of this transformational time. The accessibility of these tools creates opportunities for a common platform of communication and development that can cross many of our self-imposed barriers and offers a path to collaboration and innovation. Design education is unique and distinct from that which is practiced by most other disciplines. As such, we have the opportunity to

use the technology of our time to reach out beyond our silos and lead the way to an enriched educational experience.
The rising majority of our students fully embrace new technologies (AR, VR, AI, Social media, instant information and development tools both hard and soft) and anticipate future technologies not yet invented.

Throughout this project, the accessibility and “usability” of technology that were once the stumbling blocks of curriculum have become a stepping stone to creating best practices. By collaborating with industry experts, our students were able to leap past many of the traditional technological barriers, giving them the means and expertise to design in a fluid and intuitive way. This paper suggests a step and a process that enhances the educational experience of our students and suggests future directions for design. Partnering with industry experts (and spectacular designers) have afforded us the opportunity to examine our curriculum and extract, retain and transform key elements to enrich process and initiate meaningful output.

9. REFERENCES

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