A Flexible, Portable Making Solution to Enable Hands-On Learning with Additive Manufacturing in Cornerstone Engineering Design

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ABSTRACT

Additive manufacturing, colloquially 3D printing, is rising in prominence as a tool to support hands-on "making" education in cornerstone engineering design. While many universities are implementing centrally-located facilities to process printed designs for students, such centers often limit student access to the printers. This, in turn, limits a student's ability to understand how the manufacturing process influences the viability of printing their digital design. To address this concern, this paper discusses the creation of a flexible, portable making solution that offers students the chance to gain familiarity with the 3D printing process in a way that complements the high throughput offered by centrally located facilities. The proposed making solution incorporates low-cost equipment intended to expose students to a variety of elements associated with 3D printing, including digital design, 3D scanning, print preparation, material extrusion, and manufacturability constraints. The integration of the proposed solution with existing manufacturing lessons and faculty skillsets is also discussed.

1. MOTIVATION AND BACKGROUND

Additive manufacturing (AM, or 3D printing) technology is quickly becoming a common sight in cornerstone engineering design courses [1,2]. The reason is twofold: (i) AM is set to be a dominant tool for end-use manufacturing (and thus it benefits engineering students to be exposed as soon in their careers as possible) and (ii) low-cost AM systems can enable rapid prototyping and iteration in the design process, while dovetailing well with computer-aided design (CAD) skills also learned in cornerstone design courses. Learning institutions are increasingly investing in student access to AM, from single desktop-scale systems in a classroom to large dedicated AM spaces such as MakerBot Innovation Centers [3]. Reviews show that, overwhelmingly, spaces are often located in a fixed, centralized location, such as a library [4,5] or even through so-called "3D printing vending machines" [6,7]. However, such approaches limit learning to a single location and thus a single context. As situated cognition suggests, this may limit the potential for learning due to the interconnect between knowledge formation and the social, cultural and physical contexts in which it was performed [8]. As an alternative to these existing forms of access, this paper discusses the design and implementation of a self-contained, transportable maker cart system, to engage cornerstone engineering design students with AM's design opportunities.

The portability of the system discussed in this paper makes it capable of both formal and informal learning contexts and allows students to directly observe and reflect on the manufacturability of their designs. Similar, but less extensive, carts have been steadily growing in popularity among libraries and K-12 institutions across the nation [9–11]; however, they are often limited to spectacle, without proper curriculum to support their use. Section 2 of this paper describes in more detail the design of the maker cart system, including the key components included in the system and how they support design and AM learning. Section 3 discusses how the system integrates with the existing cornerstone design course curriculum, including activities, lesson plans, and support via hands-on demonstration pieces. Finally, Section 4 offers concluding thoughts for future research and evaluation.

2. DESIGN AND CREATION OF THE MAKING SOLUTION

In order to address the need for a complete, fully interactive, yet easy-to-use printing system in a cornerstone engineering design course, a final solution was developed over the course of several semesters. This development process included initial iterations created by two separate capstone design teams, with undergraduate research volunteers providing the final touches for design and construction. The result is a system dubbed the “Nittany Build Box (NBB).” The NBB was designed to account for lessons learned from similar 3D printing vending machines. The system includes numerous pieces of equipment (detailed in Sections 2.1-2.5) in a mobile cart-like setup. This enables easy transportation between classrooms as needed by instructors. Additionally, the NBB includes a clear acrylic enclosure to reduce the likelihood of user injury and system damage during operation. Each supporting piece of equipment was specifically chosen to emphasize a different element of AM and its role in engineering design.

Figure 1. Final "Nittany Build Box" with Supporting Units (1. Extrusion, 2. Scanning, 3. Print Preparation, 4. Printing, and 5. Showcase)

2.1. Extrusion Unit

While the focal point of the NBB is the included desktop-scale printer, it is beneficial to include a separate unit that clearly explains the concept of material extrusion to students prior to working with the printer. To that end, each NBB cart includes two so-called “3D printing pens.” Each of these demonstrates how thermoplastic filament is fed through counter-rotating rollers into a heated chamber before being extruded out of the pen’s nozzle. These basics allow students to gain a more in-depth view of the potential pitfalls of material extrusion prior to moving to printing. Such pitfalls include filament jamming and inconsistent extrusion volumes. It also enables them to quickly and easily investigate the extrusion properties of different filament types (e.g., PLA vs. ABS) to expand their material understanding. The pens included in the NBB are from the company Soyan and sell for less than $20 each, which enables easy replacement in case the pens break during operation.

2.2.Scanning Unit

One of the main advantages of AM in practice is the ability to cost-effectively customize products for a single user, owing to the fact that AM requires no tooling to produce parts. 3D scanners are often used to create such customized geometries. As with the cost of desktop AM, 3D scanners are becoming more affordable and have finally approached a price-point where they can be included in a low-cost system solution like the NBB. The scanners included in the NBB are the Matter and Form V1 scanners and sell for under $200 each. While not as robust as higher quality industrial scanners, the small turntable-style scanners successfully enable students to gain hands-on experience with 3D scanning (as shown in Figure 2) and produce scans of sufficient quality that they can then be imported for printing, should the students desire.

2.3.Print Preparation Unit

As with any AM system, the printers included in the NBB require students to perform several print preparation steps prior to building their final part. To support this phase, each NBB system contains a laptop computer (in this case, a Lenovo ThinkPad X1) stored in one of the drawers. Because the system is focused primarily on print preparation, and not design creation with CAD software, the included laptops do not require extensive processing power. Each laptop that supports the NBB systems includes a copy of Cura, a commonly used, open-source print preparation and slicing software (seen in Figure 2). Within this software, students can manipulate their desired geometry for printing; this includes changing the object's position on the build tray, its orientation, and its scale. Additionally, advanced users can adjust specific printing parameters, including layer thickness, nozzle temperature, and support material use. However, as the NBB is intended for novice users, a custom print configuration is used by default that has been tested to maximize the odds of print success with the material and printer in the NBB.

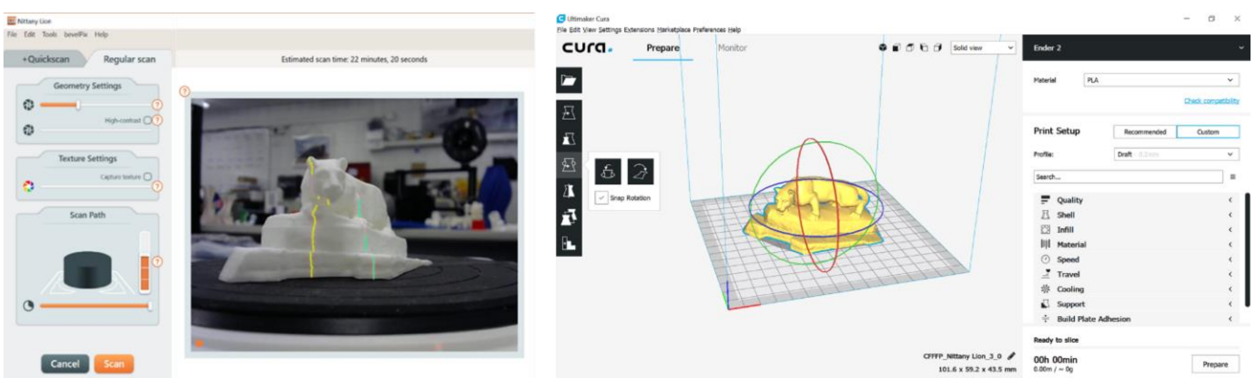

Figure 2. Scanning Software Interface (left) and Print Preparation Interface (right)

2.4.Printing Unit

Each NBB system includes one desktop-scale material extrusion printer. This printer serves as the focal point of the system and enables student prototyping. While the printing chamber in the NBB is designed in such a way that it could accommodate a variety of different printer types, this initial iteration sought to include a low-cost, open-source system that could easily be purchased by students should they desire to continue their 3D printing activities after completing the cornerstone engineering course. The specific printer selected was the Creality 3D Ender 2 machine, which retails for under $200. While the build volume of the system is relatively limited (150×150×200mm), it allows for extensive modification in order to ensure that it meets the educational context that it is being deployed in. Additionally, key components of the system, including motors, belts, extruder, build plate, etc., are easily visible due to the design of the machine. This facilitates student learning as they can clearly observe how the different printer components interact to create the final printed part. This is in stark contrast to other more expensive desktop printers, which focus on user accessibility above all, leading to a "black box" type printer.

2.5.Showcase Unit

Finally, built into the side of the NBB is a small display gallery filled with a carefully curated selection of parts. Each of the included parts is intended to showcase either (i) a design advantage of AM (e.g., geometric complexity, customization, printed assemblies) or (ii) a manufacturing consideration of AM (e.g., self-supporting angles, infill density, surface finish). Attached to each part is an informational tag that includes both basic characteristics of the build (e.g. print time, print material, print mass), as well as specifying the key design or manufacturing element that the piece is intended to communicate. By including these tags with each piece, it becomes easier for students to make a clear connection between the design and manufacturing process with AM, rather than simply observing the superficial characteristics of each included part. Additional space is included in the showcase to accommodate exceptional parts created by students in the cornerstone design course to use as examples for future semesters.

3. INTEGRATION WITH EXISTING COURSE DESIGN

Recently, six learning modules were developed by an interdisciplinary team of faculty to support core student outcomes of the cornerstone engineering design course. Of particular interest for utilization of the mobile cart is the student outcome – "Students will gain experience in hands-on fabrication while developing a maker mindset" – and the corresponding learning module centered on Making.

3.1.Connection to Manufacturing Lessons and Activities

The Making module's third lesson overviews additive manufacturing, focusing specifically on material extrusion—a technique readily available to students at the university. To support faculty in teaching the additive manufacturing lesson, teaching materials were developed, including a PowerPoint presentation and a detailed walk-through document for translation of a 3D model to STL file to sliced file for printing. Additionally, faculty have been provided detailed guidelines on integration of NBB equipment into the lesson. For instance, students are encouraged to experiment with the 3D printing pens, exploring the benefits (quick and accessible) and drawbacks (difficult to precisely control) of this technique as compared to a 3D printer. Additionally, a quick 3D print (typically around 30 minutes or less) runs while the lesson proceeds so that students can observe the process from start to finish. In this way, students are able to identify key elements of material extrusion, such as the use of support materials and build plate adhesion. While the use of the 3D printer and 3D printing pen can help students see how to prototype a physical component from their own vision or 3D model, the use of a 3D scanner shows them how they might be able to design a part to interface with an already existing component.

In addition to the equipment to support 3D printing, the display box with 3D printed artifacts provides an interactive and engaging method for students to learn about the opportunities and restrictions of material extrusion. While the instructor discusses specific examples of opportunities and restrictions, corresponding example parts can be passed amongst the students. The sheet attached to each part serves as a quick reference of the important lesson (e.g., example of printed assembly or effect of warping) to be gleaned from each example.

3.2.Faculty Support to Promote System Use

To facilitate use of the NBBs in the classroom, a detailed guide and series of one-pagers for major components (i.e., 3D printer, 3D printing pen, scanner with software) were designed and included with each NBB. Examples of two of these one-pagers are provided in Figure 3. The documents were designed to be highly illustrative to simplify use. The one-pagers provide at-a-glance best practices for the equipment, while the guide provides more information, particularly in the case of errors (print fails to adhere to the build plate, the print head is clogged with filament).

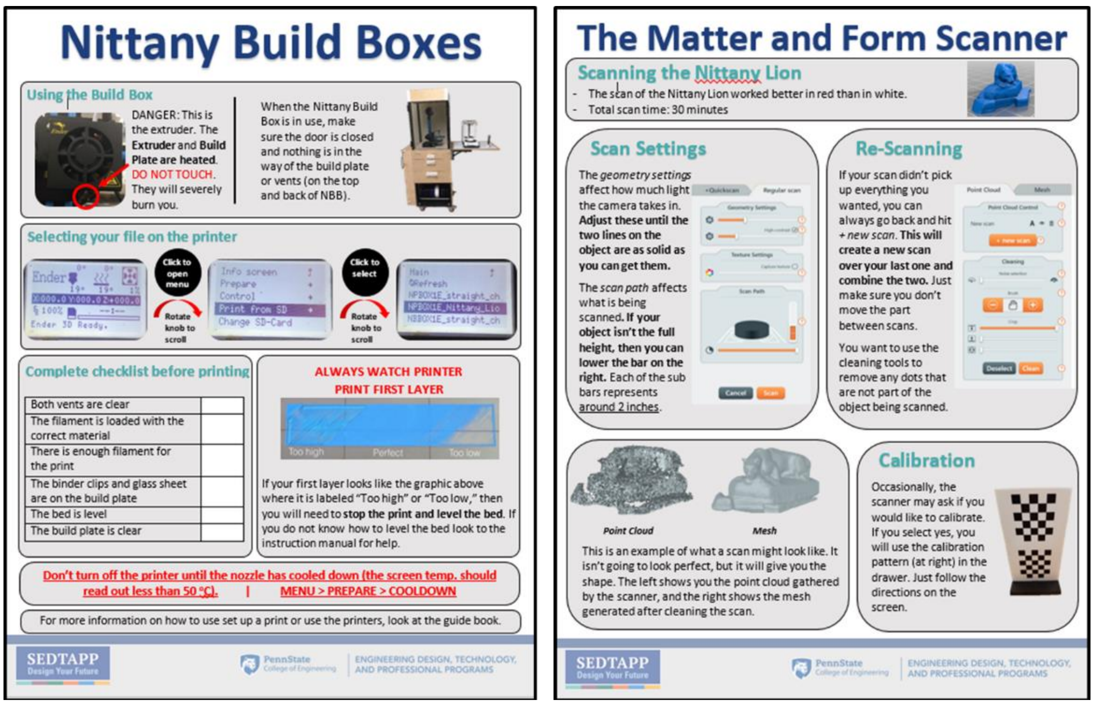

Figure 3. Supporting Documentation to Facilitate Ease-of-Use

In addition to the documentation, faculty received training on the practical integration of the NBB into the classroom, overviewing proper use of the equipment and demonstrating best practices in managing potential issues (e.g., how to load or unload filament, how to level the print bed). In future systems, this training protocol will be integrated into the standard training provided to the course Make Space Assistants (i.e., undergraduate students who have successfully completed the course and return as paid assistants in the classroom) at the start of each semester. Key Make Space Assistants will receive additional, in-depth training to take on responsibility for equipment upkeep and ensuring the NBBs remain in working condition. In this manner, the NBB will truly become a "plug and play" learning tool for the cornerstone engineering design course.

4. CONCLUSIONS AND FUTURE WORK

In this paper, the authors have demonstrated the creation and integration of a mobile making solution, the NBB, to support a cornerstone engineering design course. The proposed solution includes five separate units (extrusion, scanning, print preparation, printing, and showcase), each of which contributes to educating students in design opportunities and manufacturing considerations associated with AM. The hope is that, through the NBB system, it will be possible to offer students a more hands-on approach to AM education than is allowed for by centrally-located, on-campus 3D printing facilities intended to manufacture parts at large-scale. Examples of integration with existing lessons and curricular content were also discussed in efforts to show how the NBB system can be a sustainable solution in the years to come for faculty of all skill-sets.

While the initial informal instructor and student feedback to the NBB system is promising, extensive evaluation of system use and student learning is necessary. For example, many existing "3D printing vending machines" have since ceased operation, due to challenges with system repair and upkeep; it will be interesting to see if the approach taken with the NBB system enables a longer usable lifespan than these other solutions. Additionally, formal feedback will be solicited from students and faculty to identify opportunities for increased ease-of-use and component quality in the NBB system. Finally, a formal study will be conducted to investigate changes in students' design and manufacturing self-efficacy after exposure to the NBB system during a semester.

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