Automating Aspects of 3D Printer Management with Coding and Project Management Software

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Introduction

The advent of makerspaces has brought with it the democratization of innovation [1]. Access to rapid fabrication technology has led to an era of grassroots research and development that is unrestricted to the general public. One of the most accessible methods of rapid fabrication is 3D printing, a form of additive manufacturing that allows users to materialize a 3D model layer by layer with a variety of techniques.

Previous studies of makerspaces [2] have shown how access and interaction with 3D printing technology not only facilitates the innovative design process, but also increases user engagement, user experience, and number of returning users. However, many makerspaces must address the issue of user access and management for tools, space and machinery – such as 3D printers – to ensure these items are only accessed by designated/appropriate parties, i.e. trained users that can be held responsible [3]. Current 3D printing management software is highly automated and creates distance between the user and the technology [4]. This hands-off, "click-and-print" approach is commonly used for large scale 3D printing (e.g., print farms), where the value lies in easily obtaining an end product. However, this approach is inconsistent with the core values of academic makerspaces, which promote a hands-on manufacturing approach that often compliments components of an engineering curriculum [5].

To address this issue, we developed a custom 3D print system that enables the Makerspace to monitor, record and display specific 3D printer operations while maximizing user interaction with the additive manufacturing process. This solution utilizes commercially available work management software (i.e., Monday.com) along with our custom 3D printer firmware and backend server. The resulting system allows Makerspace users to be fully involved in the 3D printing process, including model slicing, printer preparation (cleaning off the print bed, checking there is sufficient filament for the job), uploading the sliced file to the printer, starting the print, and postprocessing. This level of engagement gives students invaluable insight into how the machine functions, which leads to more insight towards the 3D printing *design* process, i.e., Design for Additive Manufacturing (DfAM) [6,7]. A secondary effect of this system is that it relieves Makerspace employees from the duties of 3D printing preparation and allows them instead to focus on more meaningful tasks, i.e., providing design advice, installing new filament spools, performing maintenance on machines, etc.

3D Print Lab Structure

The NJIT Makerspace is a 21,000 sq. ft. rapid prototyping and industrial manufacturing facility centrally located on campus that serves all members of the university's community in their fabrication efforts.

Our 3D printing lab, called the Stereolithographic Technology Lab (STL) is equipped with 19 Ultimaker FDM 3D printers of various sizes and 2 Formlabs SLA resin printers. The most popular printers are the standard FDM Ultimaker models, which produce over 2,000 prints per year.

The layout of the lab is designed to encourage makerspace users to engage in most aspects of the additive process themselves, including creating 3D CAD files, slicing 3D models and preparing printers for print jobs. To this effect, we've installed desktop stations in the lab that are equipped with the software required for modeling and slicing (Solidworks, Autocad, Fusion 360 and Cura). In addition, beside each printer we place a printer cleanup/maintenance kit, which includes a putty knife for removing prints, isopropyl alcohol, hairspray (for ensuring print adhesion to the print bed), etc. Finally, we have a post processing

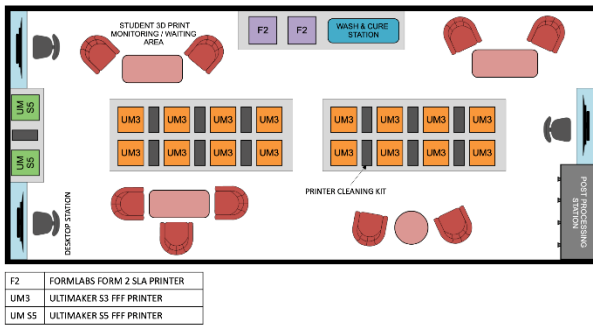station which includes various pliers, sandpaper sheets, files and picks.

Fig.1 Diagram and photo of "Self-serve" 3D printing area at the NJIT Makerspace. Printers and computers are easily accessible for members

Naturally, the 3D printing process is not perfect and print failures occur, this often requires intervention and assistance from the Makerspace staff. Therefore, it is necessary for our staff to keep track of users, printer usage, filament consumption and print status (i.e., Print in Progress, Print Complete, Printer Available for Use, etc.).

In this paper, we outline a software solution for effective 3D print management that minimizes Makerspace staff intervention and maximizes user engagement with the 3D manufacturing process.

Management System Architecture

As discussed, our 3D printing management system consists of three main subsystems: a custom modified version of the 3D printer firmware (in this case, Ultimaker printer firmware), a work management software (i.e., Monday.com API) , and a backend server (i.e. NodeJS running Express). The Ultimaker 3 firmware is written fully in Python and can be updated using SSH/SCP[1]. The Monday.com API is a GraphQL API used to get and set information from our Monday.com boards. Our backend NodeJS server is the main point of contact between these three services, and computes updated information for the

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[1] SSH being "Secure Shell Protocol", which allows us to remotely connect to the machine, and SCP being the "Secure

system (in this case, update the filament usage). It also has interaction with our user database and other backend services. This is especially useful for future plans for the system (outlined at the end of the paper).

A. *Ultimaker Firmware – LED Controller*

The Ultimaker 3 firmware is mostly written in Python, which can be accessed by enabling developer mode on the physical unit, and then accessing the machine via SSH. From there, you can see everything the printer has to offer from the API endpoints to the services that manage the printer itself. From here, we are interested in two things: a file called mainLightingController.py (which controls the lights around the frame of the 3D printer), and the method to have access to the printer's properties. From here, we wanted to change the color of the LEDs around the printer's frame to reflect the status of the printer (stored in the printer's properties as a key called "status"). For changing the colors, we had to first ensure that the lighting controller knew what the current state of the 3D printer was. This state can be one of the following options: idle (the printer is sitting idle- you can set up a print in this state), printing (the printer is mid print and in use), maintenance (the printer is in a state where you are actively changing anything [temperature, changing filaments, etc.]. You cannot start a new print at this time), error (the printer encountered some sort of error and had to stop), wait_cleanup (the current print is done and awaiting removal from the print bed). Then, we decided which colors would be easiest to identify for each state. For example, as seen in Fig. 2, we chose a light green for the idle state. In its simplest form, we usually think of a green as "good," "go," or "available" so we chose that as the color that students can easily see as "this printer is available." Similarly, we chose red for a machine with an error. After that, we decided yellow should represent maintenance as that color is usually thought of as "caution" or something of the like. For printing, we decided to make the printers a light blue simply for aesthetic purposes. Finally, we chose a purple for "print awaiting to be removed" so that it would be a distinct and easy color for the staff to see what prints need to be removed. This is the most basic implementation of the LED controller, in reality you can queue many effects such as blinking, fading, color cycling and more. We just wanted to keep it simple so that it was easy to understand from both a student and a staff perspective. Below is a screenshot of the code changed in the Ultimaker 3 firmware:

Copy" command, which allows you to download and upload files securely from one machine to another.
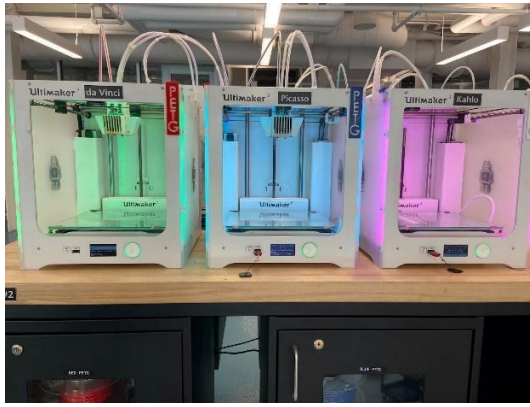
Fig.2 *Ultimaker 3 3D printers displaying green, blue and purple to indicate an available printer, a print in progress and a completed print, respectively (red to indicate error not shown)*

B. *Ultimaker Firmware – Filament Controller*

We track filament consumption using an automated program that was developed to integrate with our existing print management system using Monday.com.

Fig.3 *Monday.com "Self-Serve 3D Printing" board, showing the name of the member printing, status of the print, name of the print and part weight in grams*

Using Monday.com, we set up a designated board to keep track of all running prints, shown in Fig. 3. Among other information tracked on that board, we have a column for the printer's name and the print's weight. In addition to that, the Ultimaker 3 comes with an API that can return information on the current 3D print. The one field we are interested in here is "Progress." Progress is a percentage value (represented in decimal form) given to a print based on the number of steps completed. For example, if 500/1000 steps were completed, progress would return 0.5. We have modified the base Ultimaker firmware to work as follows: when a print is completed, we ping an endpoint on our backend at:

```
http://<backend url and
port>/printers/syncWeights?printer=<PRINTER_NAME>&prog=
<PROGRESS>
```

After that, our backend will send an API query to the Monday board to get the expected weight of the print (pictured below, from our development environment).

Next, we multiply the expected weight by the "Progress" value to obtain the instantaneous print weight:

$$W_{inst} = Progress \times W_{fin} \tag{1}$$

where,

$W_{inst} = Instantaneous\ Print\ Weight$
$W_{fin} = Expected\ Final\ Print\ Weight$

We then update our Monday board that contains the total weight for each printer, and subtract that new value we got, shown in Fig. 4. The entirety of this sequence is outlined in Fig. 5.

Fig.4 *Monday.com "Ultimaker Filament" board, which tracks filament type, color and weight for each printer*

As an example, if a print on our printer named "Hamilton" was finished completely, and it was expected to use 200 grams of filament, it would send a request with the query: "`?printer=Hamilton&prog=1.0`" to our backend. Since it was fully complete, the weight to subtract would be: 200 x 1.0 = 200. The backend would get the current weight of the spool loaded onto Hamilton (from Monday) and update it to be -200.0 from what it was originally. If we had the same situation, but the print errored halfway through, the weight would be updated to 200*0.5 = 100.0 and get subtracted from the total weight.
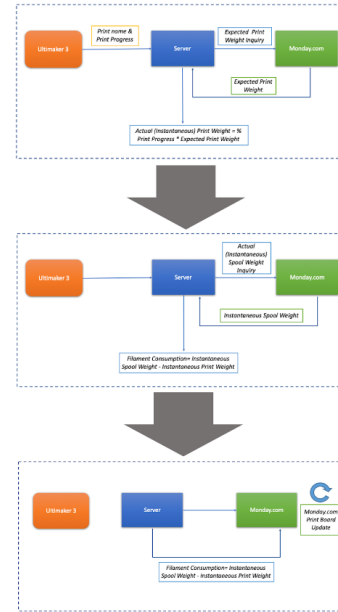

Fig.5 *Communication sequence between 3D printer, backend server and Monday.com*

Consumer Research Survey

In order to fully assess the advantages this style of print management provides, the NJIT Makerspace conducted a survey on NJIT students to analyze the habits and experiences of students utilizing the self-serve 3D printing stations. The survey consisted of a six section questionnaire that interviewed respondents on their use of 3D printers, their previous experience with 3D printing,

and their experience with the NJIT Makerspace 3D printers.

According to the survey results, which reached 222 students, roughly 70 percent of students reported that they preferred a hands-on approach to 3D printing over a "click-and-print" model offered by commercial 3D print management software, seen in the following figure.
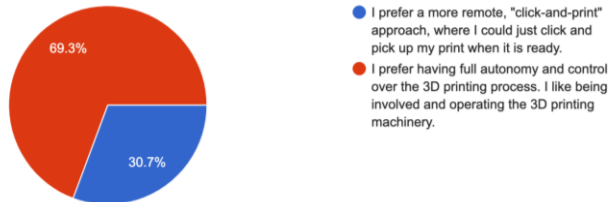

Fig.6 Graphical representation of student preference for hands-on vs. hands-off 3D printing approach

When asked about whether or not students gained valuable insight into 3D printing after using the hands-on self-serve 3D printers at the NJIT Makerspace, roughly 93 percent of respondents reported becoming more comfortable with the 3D printing process, seen in the following figure.
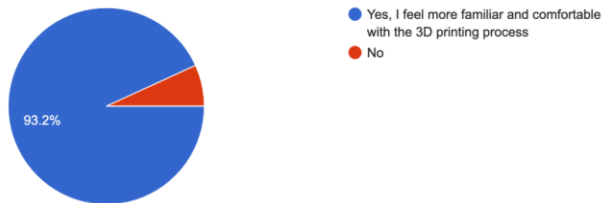

Fig.7 Graphical representation of student comfort with 3D printing for hands-on vs. hands-off 3D printing approach

These results exhibit a propensity for a hands-on 3D printing experience among our student respondents. Despite the favorable survey results, The NJIT Makerspace self-guided 3D printing process still requires some refinement. When asked whether the NJIT Makerspace's self-serve printing area was easy and intuitive to use on their first printing attempt, a 52% majority stated that they needed some assistance. The full survey questions along with the results is included in the addendum of this paper.
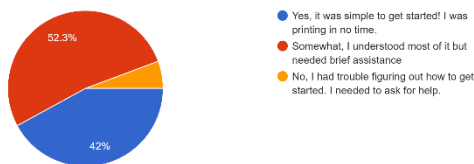

Fig.8 Graphical representation of student ease-of-use during their first attempt with the self-serve 3D printing area

Future Developments

Plans for future development include having the printer automatically query the filament tracking board on Monday.com to automatically ensure that the printer has the sufficient filament to complete a print prior to starting the print. Additionally, we hope to eventually include student recognition software that would verify that a student has taken the appropriate training courses required to use the printers. Eventually, we plan to develop a CURA plugin that allows students to slice their files and submit it for design review and consulting. If a print fails, this system would also allow us to easily issue a reprint. We plan to integrate these features into our existing backend dashboard (a NodeJS server running Express). Finally, the survey results shown in Fig. 8 suggest that elements of the self-serve printing area can be better explained during user training before use and/or visually in that area of the makerspace.
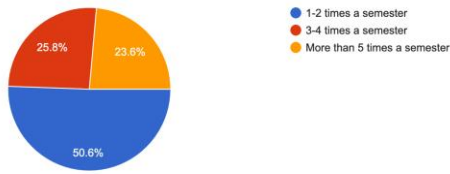
Conclusion

In this paper, we discuss the development of a custom 3D print management system that would automate 3D print management while maximizing user interaction with the additive manufacturing process. Utilizing work management software, modified 3D printer firmware and a backend server, we developed a fully integrated 3D print system that allows users to autonomously operate the 3D printers with minimal involvement from the Makerspace staff. We program hardware and software elements, such as changing LED light colors that signal printer status, and program computations that calculate filament usage and update relevant Monday.com boards. Makerspace users are easily able to identify which printers are available for use based on the printer's LED light color. This also allows Makerspace staff to easily count printer availability and printer error. The filament management system automatically computes and updates 3D print weights, which allows for easy print management. All of this helps us not only run an efficient Makerspace, but also encourages a hands-on user approach to additive manufacturing processes. A survey of students who utilize our Makerspace's self-serve 3D printing area revealed that the majority of these students preferred and benefitted from a hands-on approach to 3D printing, and our makerspace provided that experience in an approachable manner. Our goal at the NJIT Makerspace is to encourage hands-on approach to design and manufacturing so that we can develop well-rounded and insightful engineers and inspire the next generation of creators and innovators.
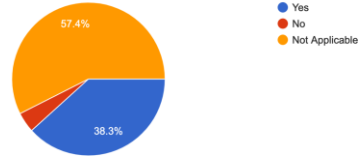
Addendum

The following section outlines the questions and results for the NJIT Makerspace 3D printing survey. The survey was sent to the entire NJIT student body via mass email distribution. Students were incentivized to participate in this research study for free 3D printing credit. The survey was designed in Google Forms with conditional logic to ensure that questions are relevant to each respondent. All the questions, along with their responses, are shown below:
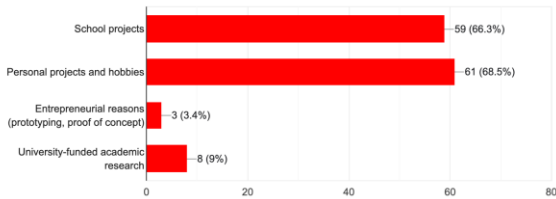
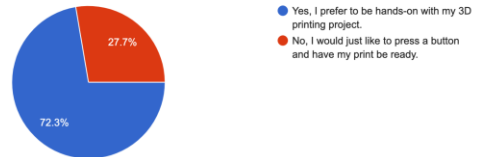**On average, how often do you use the Makerspace 3D printers?**
89 responses

- 1-2 times a semester
- 3-4 times a semester
- More than 5 times a semester

25.8% 23.6% 50.6%

What do you generally use the Makerspace 3D printers for? (Select all that apply)
89 responses

- School projects — 59 (66.3%)
- Personal projects and hobbies — 61 (68.5%)
- Entrepreneurial reasons (prototyping, proof of concept) — 3 (3.4%)
- University-funded academic research — 8 (9%)

Which aspects of 3D printing are most important to you? (Choose up to 2)
89 responses

- Ease of use — 43 (48.3%)
- Cost — 52 (58.4%)
- Print Quality — 48 (53.9%)
- Turn around time — 16 (18%)
- The experience — 14 (15.7%)

Did you have hands-on 3D printing experience prior to using the self-serve 3D printing station at the NJIT Makerspace? (i.e. were you ever responsible for operating a 3D printer?)
89 responses

- Yes
- No

47.2% 52.8%

Have you ever used a click-to-print 3D print management software like Printeros, Octoprint, Repetier, or AstroPrint?
47 responses

- Yes
- No
- Slic3r
- Yes I use 3dprinteros with my personal printer at home its really good.

66% 29.8%

Have you ever utilized a 3D printing service (3D Hubs, Xometry, etc.) to have a part 3D printed for you (i.e. you were not responsible for operating the printer)?
47 responses

- Yes
- No

83% 17%

Did you find these 3D print management software or services easy to use?
47 responses

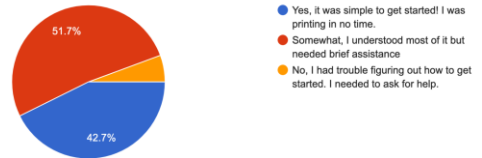- Yes
- No
- Not Applicable

57.4% 38.3%

In your experience, do you prefer hands-on method to 3D printing (like the NJIT self-serve 3D printing stations), as compared to the "click-and-...ffered by the above 3D print management software?
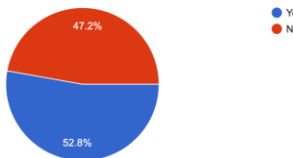47 responses

- Yes, I prefer to be hands-on with my 3D printing project.
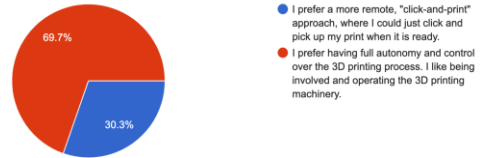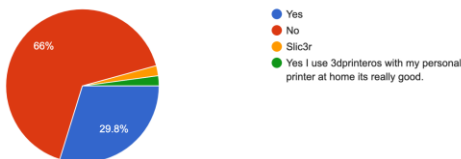- No, I would just like to press a button and have my print be ready.

27.7% 72.3%

Did you find the NJIT Makerspace self-serve 3D printing station easy and intuitive to use the first time you used it?
89 responses

- Yes, it was simple to get started! I was printing in no time.
- Somewhat, I understood most of it but needed brief assistance
- No, I had trouble figuring out how to get started. I needed to ask for help.
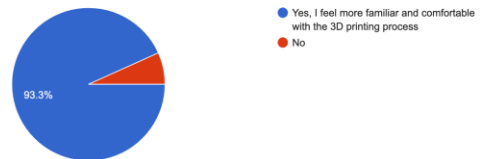
51.7% 42.7%

If you could choose, would you prefer a more remote, hands-off approach to 3D printing, or do you prefer having full control and involvement in the 3D printing process?
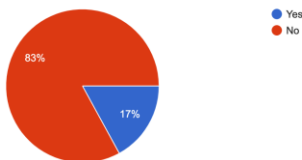89 responses

- I prefer a more remote, "click-and-print" approach, where I could just click and pick up my print when it is ready.
- I prefer having full autonomy and control over the 3D printing process. I like being involved and operating the 3D printing machinery.

69.7% 30.3%

After using the Makerspace's self-serve 3D printing stations, do you feel more comfortable with the 3D printing process?
89 responses

- Yes, I feel more familiar and comfortable with the 3D printing process
- No

93.3%

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