3D Printing as an Enabling Platform for Cross-Disciplinary Undergraduate Engineering Education and Research

Michael Kinsler[1], Colin McGill[2], Giovanni Rodriguez[2], William Berrios[2], Jeremy Chow[2], Amelito Enriquez[2], Paul Grams[3], Xiaorong Zhang[1], Hamid Mahmoodi[1], Wenshen Pong[1] and Kwok Siong Teh[1].

[1]School of Engineering, San Francisco State University, San Francisco, CA/ [2]Cañada Community College, Redwood City, CA/ [3]NASA Ames Research Center, Moffett Field, Mountain View, CA.

Abstract

Expanding undergraduate students' learning beyond the traditional classroom and exposing them early on to research training or hands on project have been proven to be an effective means to prepare them to be engaged learners and sophisticated engineers. Faced with increasingly complex engineering problems that are inextricably intertwined across engineering disciplines, an engineer's traditional comfort zone of 'individual discipline' no longer exists. In present day's context, an engineer needs to possess cross-disciplinary skills in order to effectively tackle complex engineering problems that are multidisciplinary in nature. For institutes of higher learning, this makes the task of creating meaningful and educationally relevant cross-disciplinary student research projects all the more challenging yet highly impactful if done successfully. In this paper, we describe a cross-disciplinary project where 3D printing and specifically, the conceptualization and prototyping of a temperature-controlled enclosure for a 3D printer, serve as an enabling platform to catalyze learning of the essentials of team-based, interdisciplinary engineering research and development. The goals of the project are: (i) to investigate the influence of a controlled temperature environment on the print quality of 3D printed parts, and to optimize the print quality accordingly; (ii) to allow beginning engineering students with little prior engineering training and 3D printing knowledge to complete a product development cycle of problem definition, literature research, design concept generation, prototyping, and testing under guidance. To this end, a team of four community college mechanical engineering sophomores, working under a NASA Curriculum Improvement Partnership Award for Integration of Research into Curriculum (CiPAIR) grant, were tasked with conceptualizing, designing, and prototyping a closed-loop temperature-controlled enclosure that encased a 3D printer using commercially available parts, as well as testing the properties of parts printed in such a controlled environment. Under the supervision of a graduate student mentor and a faculty mentor, the team learned mechanical design using SolidWorks, material selection, hands on metal and plastics fabrication, heat transfer, as well as microcontroller programming using Arduino to build a temperature-controlled enclosure made of acrylics with built-in heating and cooling elements. Parts made of poly-lactic acid were printed and tested with and without temperature control. Various quantitative tests were performed on parts printed in a non-enclosed versus a temperature-controlled, enclosed environment—including tensile test, hardness test, and surface roughness measurement—to determine the quality of prints and the effectiveness of the enclosure. Both the tensile test and hardness measurement showed positive correlation between controlled temperature and mechanical properties of the printed poly-lactic acid. Comparing samples printed with and without temperature control, the latter allowed for the optimization of tensile strength and hardness. Specimens that were printed in a controlled temperature range of 35-37°C showed the largest improvement in both tensile strengths and hardness as compared to specimens printed without temperature control, or printed at lower or higher controlled temperatures. Exit interviews with students showed a deepening of interest in engineering as a career, a significant increase in professional confidence, and strong interest in pursuing graduate study in engineering.

1. Introduction

Three-dimensional printing is a rapidly developing technology that revolutionizes the design and fabrication process of products by increasing the speed and efficiency in which complex, three-dimensional (3D) objects can be created[1,2]. However, given the technology is relatively new, there are many aspects to 3D printing that still require optimization in order to achieve a high-quality print within a reasonable time and cost. Many 3D printers extrude the thermoplastics acrylonitrile butadiene styrene (ABS) or poly lactic acid (PLA) as print materials and create a 3D object by extruding many fine layers over one another until the object is complete[2]. These polymer thermoplastics behave similarly, yet adhere to the print bed and previous layer of material best in material-specific environmental temperatures and conditions. In order to prevent delamination and to increase the print quality, the optimal environment temperature in an 8 ft^3 enclosure is explored. A majority of current 3D printers have heated extruder heads and heated print surfaces, but these only provide local heating and cannot maintain the optimal temperature across the entire print. As a result, a temperature-controlled enclosure could be a beneficial addition to a 3D printing setup in order to increase part-to-part consistency.

Controlling and maintaining the environmental temperature during a print improves the overall quality of the print for multiple reasons. 3D-printed objects tend to have issues with interlayer adhesion if they contain more than a few layers in z-axis height. This is primarily caused by the temperature gradient between the layer on the print surface and the layer freshly deposited from the extruder. At lower z-axis ranges, the heated print bed is able to heat most layers evenly. However, beyond a certain number of layers, the temperature varies and can fail to meet the minimum temperature required for proper inter-layer adhesion. Coupled with the temperature gradient, this can lead to delamination when the printed object is complete, as well as warping of the print surface of both the main and support structures of the print. Maintaining an elevated environmental temperature reduces the possibility of warping and delamination along with improving the integrity, uniformity, and strength of printed structures. Surface finish can also be an issue with 3D printing, due to the nature of fused deposition modeling (FDM)[3], which is the most common printing method in which plastic is deposited in strings, layer by layer. Printed surfaces in direct contact with the heated bed consistently have a smoother texture and glossier appearance than surfaces not in direct contact due to the elevated temperature of the bed, which promotes reflow and hence polymer chains movement. When exposed to consistent and higher temperature throughout the duration of the print, the surface textures of all external surfaces can be improved with a more consistent and smoother surface texture. By rectifying each of these issues, a closed-loop feedback temperature controlled enclosure can prevent warping and provide a smoother surface finish, leading to higher overall print quality.

2. Project Scope

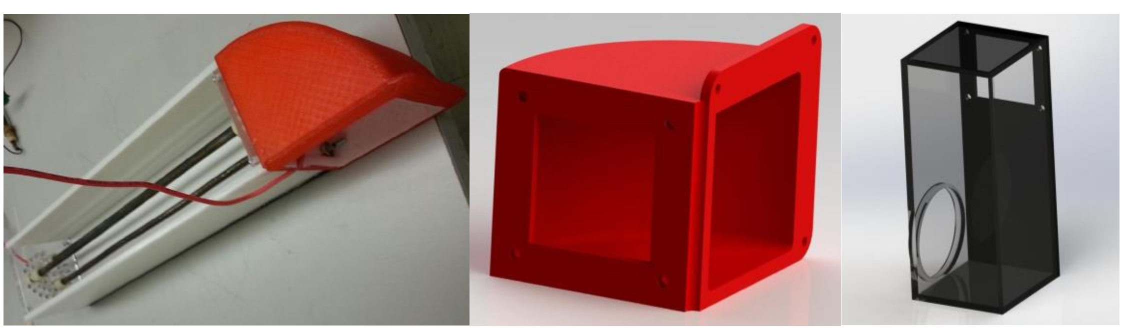
A team of four community college engineering sophomores were tasked with conceptualizing, designing, constructing, and testing a temperature controlled enclosure for a 3D printer (PunchTec Connect XL)[4]. The overarching goal of the endeavor was to determine if an enclosure, with or without active temperature control, could improve the print quality. Without active temperature control, it is reasonable to expect that an enclosure may increase print quality by minimizing convective air flow that could potentially: (i) introduce instability in the still-viscoelastic polymeric extrudate during deposition, or (ii) deposit dust/debris particles in the still-malleable print material. On the other hand, the primary rationale behind implementing active temperature control is to explore ways to reduce part warpage during and after printing. While most 3D printers with heated beds can mitigate warping effects through the completion of printing, the cooling rate after completion of the printing is generally uneven within the part. The bottom of the part which is in contact with the heated bed during and post-printing will cool at a lower rate than the sections above the bed[5]. When the part is finally removed from the bed and allowed to cool completely, residual stress through the thickness of the part will form. As such, the implementation of a temperature-controlled environment allows for slower, controlled and more uniform cooling throughout the part, and could potentially mitigate through-thickness stress gradient within the part.

The major aspects of the project included the enclosure, heating elements, environment temperature measurement, temperature control, user interface, and testing. The students' overall goal was to create an enclosure that had an intuitive user interface that allowed for a desired temperature to be set easily. Once the desired temperature was set, the enclosure would be heated to the desired temperature and be able to maintain this temperature while minimizing air movement from the heating subsystem. With the construction of the enclosure completed, the testing and actual research with regards to the effects of the enclosure could then proceed. Based on the hypothesis that controlled environment could enhance quality and properties of a print, the students determined a testing scheme that involved tensile tests, hardness tests, and surface roughness tests to elucidate the effect of temperature control on key mechanical properties.

(A) Design and Fabrication

Before building the enclosure, the students performed materials selection and developed components specifications. One of the most important areas of focus was the walls of the enclosure. The walls had to tolerate elevated temperatures while being cost-effective and transparent. It was decided that acrylic was a suitable material choice given its being capable of withstanding temperatures ranging from -40° to 60°C while maintaining its mechanical rigidity and strength. The acrylic sheets were purchased in 24 inches by 24 inches sheets with a thickness of 0.25 inches and bonded together with acrylic weld and metal *L* brackets. To facilitate access to the 3D printer within the enclosure, a door was attached to a reinforced section of the enclosure.

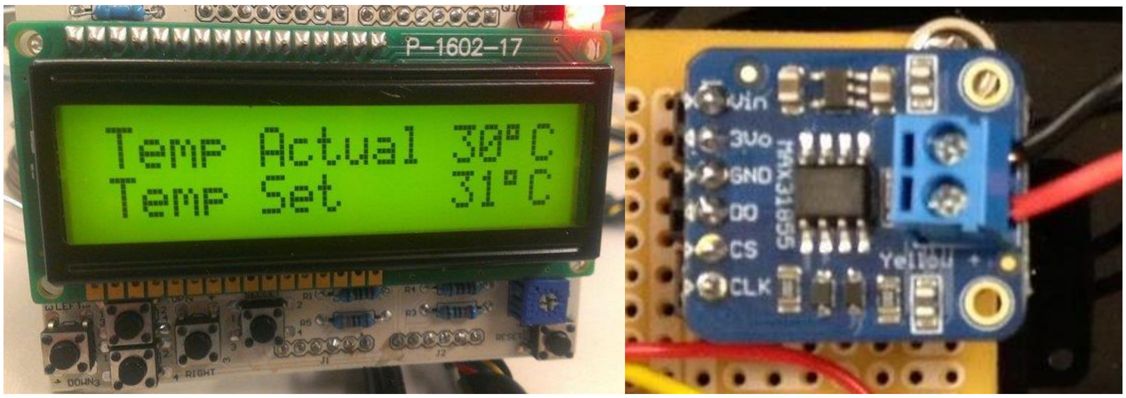
For the heating element, a product that could heat and cool in a short period of time was necessary. The team decided to use three heating elements salvaged from a toaster oven. The repurposed heating elements are powered by 120V AC which required special circuitry in order to be controlled with the Arduino microcontroller the team intended on using. The heating elements were housed in a secondary enclosure made from acrylic that was spray-coated with a ceramic coating to maintain the integrity of this secondary enclosure (Fig 1a). The heating system consists of a 12V DC CPU cooling fan to circulate air through a heated chamber containing three heating elements (Fig 1a) into the 3D printer's enclosure. The heating chamber is connected to the enclosure with a custom PLA duct (Fig 1b) and reheater duct (Fig 1c). The PLA duct was printed using the PunchTec 3D printer and the reheater system was constructed from acrylic sheets.



(**a**) (**b**) (**c**)

Figure 1. (a) Heating element, (**b**) SolidWorks drawing for the vent, (**c**) Reheater.

In order for the user to set and monitor the temperature within the enclosure, the students added an LCD Button Shield Display manufactured by LinkSprite. It contains a 16x2 character display with a green backlight, as well as five programmable buttons and one reset button (Fig 2a). To monitor the temperature inside the enclosure, a wire-style K-type thermocouple was implemented. The thermocouple output was converted to a usable signal using a Max 31855 thermocouple amplifier breakout board (Fig 2b) from Adafruit Industries. In order to control the CPU fan and the heating elements with a microcontroller, a MOSFET was implemented for power control. As previously mentioned, an Arduino microcontroller was used as the processor for the control system (Fig 3).



(**a**) (**b**)

Figure 2. (**a**) LCD button shield by LinkSprite, (**b**) Max 31855 thermocouple amplifier

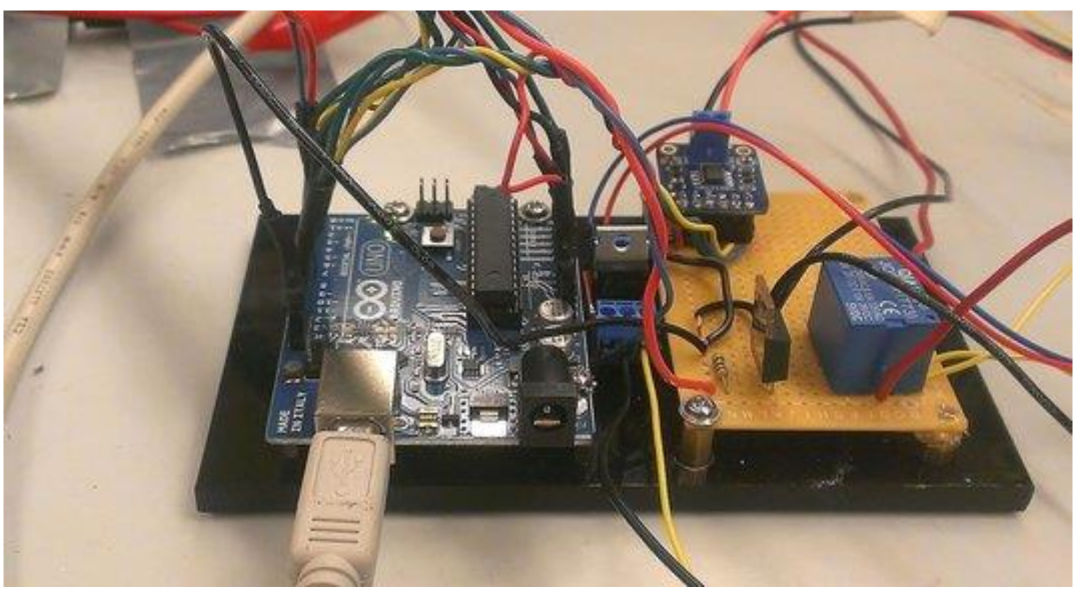


Figure 3. Arduino Uno connected to the thermocouple, LCD screen and heating system.

(B) Circuit Elements

According to the original design plan, the circuit for the heating elements was to be composed of a Power Control MOSFET. Since the heating elements require an AC current to be powered the team wanted to see if pulsing the DC power would create an artificial AC wave that would power the heating elements. This approach proved to be ineffective and left the heating elements underpowered. The team determined that this was due to the coils not receiving enough amperage. Because of this the team opted to upgrade the power supply to a 12V 30A model. However, even with the upgraded amperage, the heating coils were still under-powered. After consulting with an electrical engineer, it was determined that using AC power was necessary. For this approach to work, there needed to be a safe way for the Arduino microcontroller to control the AC current sent to the heating coils.

The new approach to control the heating coils utilized an IRF510 MOSFET which was used to switch a relay. A schematic for this circuit was created using PSpice (Fig 4). This circuit worked with a 5V DC signal sent from the Arduino microcontroller to the IRF 510. The IRF 510 then used that signal to close a circuit between the relay and a power supply, allowing roughly 12.6V to be sent to the relay. The relay we used required 12V to actuate the internal coil, which, when activated, created a magnetic field inside the relay. This magnetic field then closed an internal switch inside the relay which we used to run AC current. Once the internal switch is actuated, the AC current flowed to the heating elements. With this setup there was less potential for failure; however, the team also had less overall control of the heating elements. After some initial tests, the team concluded that further control of the heating elements was not needed, and chose the relay circuit.

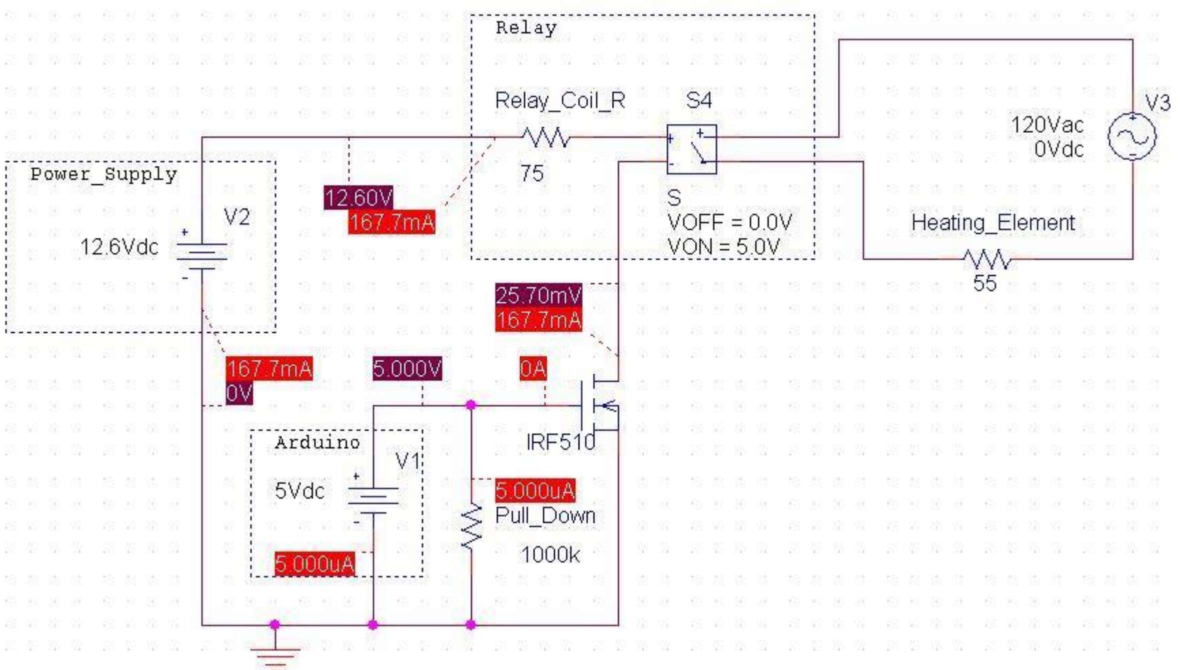


Figure 4. Relay circuit design using PSpice.

(C) Tensile Testing

By determining tensile strength it was possible to determine the important material properties of the printed parts. This provided a useful comparison and method of determining whether or not the enclosure was effective. To determine tensile strength, an Instron 3369 tensile test system was utilized. The test prints were clamped down by their ends and gradually pulled apart in an elongating manner. The data, when graphed, displayed stress vs. strain characteristics that revealed interesting trends and properties of the material.

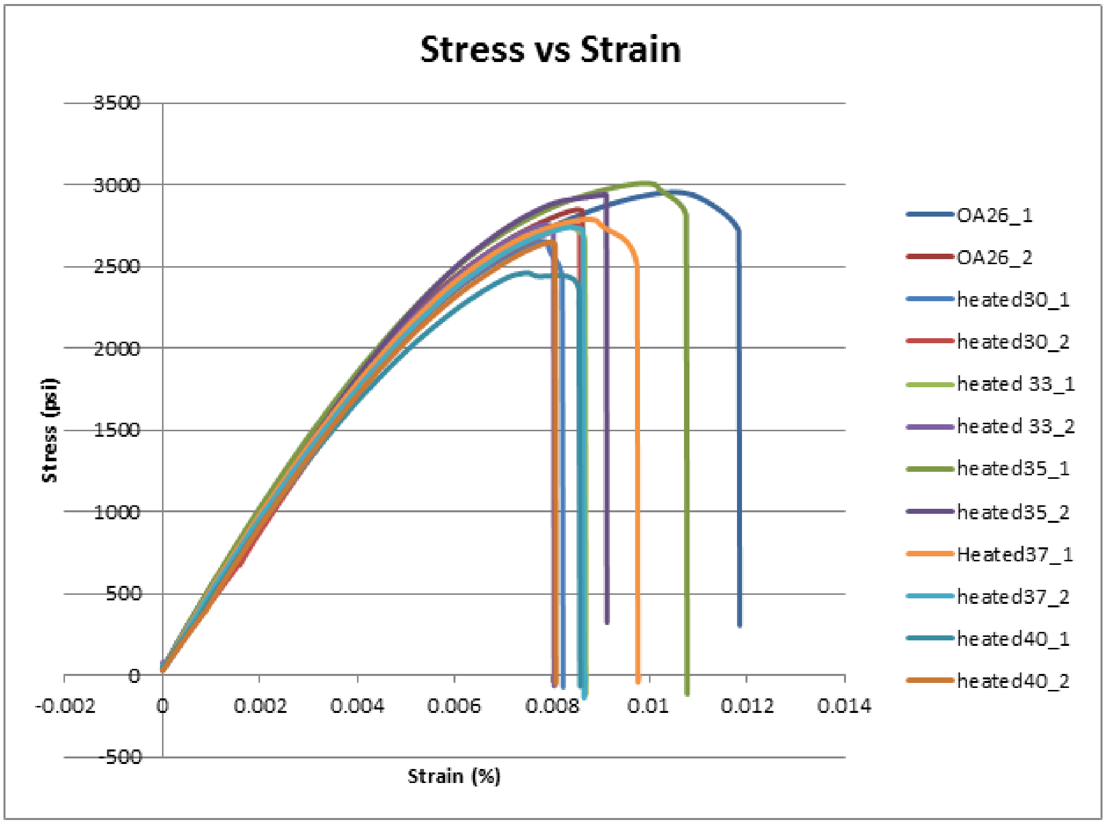


Figure 5. Tensile Test graphs of specimens

In the stress vs. strain graph (Fig 5) there are certain trends that reveal critical information about the test material. There are four stages that are revealed once a material has been tested: the elastic stage, the yielding stage, the plastic and strain hardening stage, and the necking stage. Each stage reveals a critical limit that provides important information about the material. These specimens performed differently than common polymer specimens. They experienced a significant amount of elastic behavior when compared to normal bulk PLA specimens. The 3D printed specimens presented here were printed with 20% hexagonal fill patterns. With normal bulk PLA it is typical to see significant plastic deformation, however in the presented specimens we see almost equal parts elastic and plastic deformation prior to failure. Polymers under tensile load typically deform plastically. The brittle nature of the presented specimens signifies that either the internal structure of the specimens or the heat processing of the printing process caused this material (PLA) to become significantly more brittle.

The tensile strength graph suggested that the heated enclosure increased the tensile strength a small amount at a certain temperature. There appeared to be a zenith of tensile strength values at the optimal temperature of 35°C. Beyond this temperature, the tensile strength would begin to decrease rather than increase the tensile strength of the PLA sample test print. The strongest sample which was made at 35˚C, withstood a max stress of 3009 psi at a strain of .9905%. The maximum average stress was supported by the 35˚C prints, which held a combined average 2974 psi. As mentioned, tests beyond 35˚C such as 40˚C tend to lower the tensile strength to a point even below that of the open air (26˚C) prints, which withstood an average of 2900 psi stress, the second highest value. The samples heated to 40˚C averaged a maximum stress of 2556 psi, while the samples heated to 30˚C held an average maximum stress of 2704 psi. If the temperature is above 40°C, the feeder of the 3D printer would be jammed--the plastic became too soft to be pulled from the spool. The 35˚C print could have held more stress than the other samples because of stronger lamination between layers above the heated bed due to an optimal environmental temperature. However, this did not explain why the 30˚C sample print held at least 6.8% less stress than the open-air print and 35˚C print. The 40˚C sample prints were the weakest prints out of all of the samples, which may have been caused by the environmental temperature being too high for the extruded thermoplastics to laminate and solidify correctly. It is important to note that the 35˚C prints were only capable of holding 2.5% more stress than the open-air print, which is a difference too insignificant to draw any definitive conclusions about whether the heated enclosure affects the print tensile strength.

3. Learning Aspects for Students: Research Experience

Participation in a research project during the early-to-mid college career provides a learning environment where lectures are reinforced with hands-on experiences and new topics outside of lectures are learnt. While most lab classes that are paired with lectures provide a simplified version of a true research lab environment, actually joining and working on a research project allows students to work on and explore topics outside of the normal curriculum. By allowing students to explore their own interests, the students seemed to become more interested in simply expanding their knowledge base. This includes trying to get more out of their classes by studying more and, in general, becoming more enthusiastic about learning. During the course of the project it was apparent with two of the students that they had a transition from asking “How do we fix a problem?” to “Why does this problem exist?”. This transition partially included the students performing more literature searches on their own and trying their own little experiments while trying to complete project related tasks.

This project allowed these four students to experience a research project that was directly related to their interests. Despite not being of their own conception, the project idea was determined with consideration to what is a new and interesting technology that requires some deep learning into various subjects. 3D printing fit these profile requirements very well. While the obvious project would have been to have them build a 3D printer and study how various modifications altered its performance, this would have taken too long and been outside of the allotted budget. The question was raised of whether enclosed printers produce higher quality prints due to the controlled environment. This was relatively easy to explore as it required an enclosure and a temperature controlling mechanism. The project therefore necessitated both electrical and mechanical aptitude. Seeing as how all the participants were mechanical engineering students, everyone's skill set was tested and expanded by the project. This simulated a long term research project or a new and challenging job.

Parts of this project were beyond the students class based knowledge at the time of the project. Only two of the four students had taken electrical circuit classes and their knowledge of thermodynamics was limited. Considering both thermodynamics and circuit design and construction were important for this project, the students seemed to approach the project as if it was above their skill level. Once it was demonstrated by the advisor on how to figure out what they needed to know and where to look, the students quickly picked up their work pace and enthusiasm for the project. As the project progressed the students self-regulated and almost automatically assigned or picked up specific tasks based on their skill sets and interests.

The biggest task, by far, was the construction of the electronic control unit for the project. With limited previous experience (one student had used an Arduino prior and taken a circuits class and one other had simply taken a circuits class), the students quickly realized that this needed to be the initial focus for the project. At first the students were very ambitious and were trying to work through all the electronics at once. However, from the previous experience of the advisors, the students quickly realized that breaking the electronics down into smaller projects that could be combined later was a much more efficient means of progress.

One of the initial problems that the students overcame was the heating element. The original heating element that was purchased for the project was not sufficient. While there were no calculations performed to determine this, the students devised small tests of the heating element to determine if it would be capable of heating a large enclosure. The test that the students constructed was to apply the heating element to the heatsink and measure how hot certain points (moving away from the heating element) on the heatsink became. Due to a significant temperature drop across the heatsink signified that this heating system would not work.

While the students had not been formally introduced to circuit design or thermodynamics, they were able to learn on their own in order to construct a simple experiment to test whether a component satisfied their design constraints. Alongside this test, the students also decided to implement a reheating system in order to increase the efficiency of the system. While the original design of pulling exterior air through the heating element system worked, it took too long to heat up. In order to solve this the students read about and implemented a reheating system, which is significantly more advanced topic than any of the classes had covered for any of the students.

By providing a hands on task for the students to explore that was related but more advanced than anything covered in their classes, the students were forced but internally driven to explore and conquer these more advanced topics.

4. Students' Responses and Survey Results

In order to gage the effectiveness of the summer research program, a post-completion exit survey was conducted. The survey was administered to 16 community college students, four each from the mechanical engineering, civil engineering, electrical engineering and computer engineering groups. Two sets of responses are summarized in Tables 1 and 2. While it appears that overall the projects were pleasing and useful to the students, some of the most important aspects of the projects to the students were not the actual projects themselves but more the skills and knowledge that was gained from the experiences. For example, "performing research" scored lower than "creating a poster presentation" or "working as part of a team". Skills such as technical report writing and proper presentation techniques are crucial. These skills can be the difference of high quality work being appreciated or disregarded. While projects and internships, such as the NASA CiPAIR, are platforms for skill development, they also allow for intrapersonal development. For some in this program it helped determine whether or not they wanted to go pursue a graduate degree. The students who were interested in the how and why certain results occurred and subsequently pursued information to determine those answers, were most interested in future research.

Table 1. Summary of student responses to the post-program survey measuring the perceived benefit of participating in the research internship program.

Question: As a result of your participation in the program, how much did you learn about each of the following? 1 – Nothing; 2 – A little; 3 – Some; 4 – Quite a bit; 5 – A lot.

Activity	Average Rating
Performing research	4.3
Designing/performing an experiment	4.5
Creating a work plan	4.7
Working as a part of a team	4.6

Writing a technical report	4.5
Creating a poster presentation	4.6
Making an oral presentation	4.5

Table 2. Summary of student satisfaction with the summer research internship program.

Question: Tell us how much you agree with each of the following statements. 1 – Strongly Disagree; 2 – Disagree; 3 – Neutral; 4 – Agree; 5 – Strongly Agree.

Activity	**Average Rating**
The internship program was useful.	4.6
I believe that I have the academic background and skills needed for the project.	4.4
The program has helped me prepare for transfer.	4.2
The program has helped me solidify my choice of major.	4.2
As a result of the program, I am more likely to consider graduate school.	4.0
As a result of the program, I am more likely to apply for other internships.	4.8
I am satisfied with the NASA CIPAIR Internship Program.	4.6
I would recommend this internship program to a friend.	4.8

Aside from the learning of topics that extended past their classrooms, the students learned skills that were applicable in a wide variety of situations. The program required the presentation of each group's project in both oral, written, and poster forms. For most of these students in the mechanical engineering group, barring one student who participated in the program the previous year, it was their first time presenting a research project. It should be noted that due to this group's commitment and work, they earned themselves the "Best Poster" award at the SACNAS Conference. In the post project questionnaire one student specifically called out the fact that he "had the opportunity to improve [his Solidworks] and communication/presentation skills." While the students may have presented in front of their classes for class based projects, they had never had the opportunity to present at a conference or to a large (in comparison to a standard class) audience of their peers.

Other group members felt that one of the most important lessons they learned from this project was time management. In today's world, time management seems to almost be an unimportant aspect of daily life considering the regular use of electronic devices to alert us to where we need to be. However, standard time management skills do not apply to research projects. Every project may start off with a well devised schedule, but issues always arise. Because of this, time management turns into crisis management very quickly, and the students in this group experienced this early on in the project with the heating element. While the heating element issue took longer than planned to get right, the skills learned of how to deal with issues was comprehended quickly by the group and future issues such as the heating rate seemed to be dealt with in a rapid and efficient manner without getting too far off of schedule. This is also demonstrated in Table 1 where "creating a work plan" received an average value of 4.7, the second highest result in the post-internship questionnaire.

All of the skills learned during the course of this project were focused, despite being unintentional, around preparing the students for future research positions specifically at the graduate education level. While this was a short term project, elapsing approximately 3 months, it provided the students with a chance to determine whether or not they enjoyed the research environment and if they felt that graduate study would be something they are interested in. Considering many people go into graduate study without previous research experience, this was a great opportunity for the students to figure out how to proceed in their studies. By integrating various topics (thermodynamics, heat transfer, mechanics, electrical circuits, and mechanical design) the student were shown that while they may intend on focusing in a specific area, broadening their horizons to topics outside their comfort can be fun and very interesting. However, while some of the students answered that they were now more interested in pursuing a graduate degree, some learned that graduate school may not be for them. This is signified by the fact that this aspect was rated the lowest with a score of 4.0.

5. Conclusion

Programs such as the NASA CiPAIR program provide a mutually beneficial learning environment to educators and students alike. Throughout the duration of the 3D printer enclosure project, the students advanced their knowledge beyond the theoretical level that is provided in a classroom environment. While the students are benefitting from a hands-on learning environment, the primary investigator and/or mentor to the students gets to explore topics that may not normally be pursued as the project may be too simple and short for a regular research assistant. While the enclosure for the 3D printer was a complex task it would not have otherwise been created as other lines of research (such as new advanced print materials) would be considered more impactful and economically viable. However, the enclosure proved to be beneficial for creating more uniform samples along with provided a research project that the students could experience and be involved in from start to finish.

Bibliography

1. Ahn, S. H., Montero, M., Odell, D., Roundy, S., & Wright, P. K. (2002). Anisotropic material properties of fused deposition modeling ABS. *Rapid Prototyping Journal*, *8*(4), 248-257.
2. Pham, D. T., & Gault, R. S. (1998). A comparison of rapid prototyping technologies. *International Journal of Machine Tools and Manufacture*, *38*(10), 1257-1287.
3. Boschetto, A., Giordano, V., & Veniali, F. (2013). Surface roughness prediction in fused deposition modelling by neural networks. *The International Journal of Advanced Manufacturing Technology*, *67*(9-12), 2727-2742.
4. PunchTec. Connect XL 3D printer. <http://www.punchtec.com/store/3d-printers/connect-xl/>. Accessed 2014 July 29.
5. Roberson, D. A., Espalin, D., & Wicker, R. B. (2013). 3D printer selection: A decision-making evaluation and ranking model. *Virtual and Physical Prototyping*, *8*(3), 201-212.