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Project Daedalus: An Additive Manufacturing Vending Machine

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CAD(D): Computer-aided design (and drafting)

CAM: Computer-aided manufacturing

CATIA: computer-aided design software used to create 3D-printable parts

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Introduction

This report details an Embry-Riddle research and engineering project with the primary goal of creating a fully autonomous, 3D-printing vending machine. It originally attracted a student body of 45 freshmen and sophomores. By the end of the 2016 spring term it boasted a consistent 28 to 34 freshmen and sophomores who worked within seven teams: CAD, Electrical, Logistics, Research, Software, Standards, and Structures. At its core the project was an attempt to make 3D-printing technology more accessible to a university of engineers and entrepreneurs and to those that pursue CATIA and 3D-printing as a hobby. Similar endeavors have been completed at other universities by graduate groups, but none have achieved the level of accessibility and endurance that was attempted here.

The impact of the project, however, was not limited to making 3D-printing more accessible. Its secondary goal was to cultivate future leaders in the science and engineering industries. The project catalyzed student success at Embry-Riddle by helping them to improve their various professional skills, enhance their resume by building team project experience, and find their niche at the university. It was the project's hope that making 3D printing more accessible to the student body at Embry-Riddle would in turn make it more affordable and enjoyable. As a result, students would be more inclined to interact with modeling programs such as CATIA outside of the classroom, and thus their additive manufacturing and computer-aided design skills would be improved. Students following this course of action would then likely go on to apply their new knowledge within the university, the industry and the community.

The project's structure was a mutation from a former project with a similar volume of members, and it focused on engaging a larger number of students simultaneously rather than having one group's success rely on others'. Project work was divided up into individual, manageable tasks that were expected to be taken by members as often as possible. Due to this forethought the project was able to handle its initial population of 45 individuals and make significant strides toward its goal despite the average lack of experience of its members.

Methodology

Group Structure

This project had a membership structure consisting of three levels: general members, leads and catalysts. There were eight leads in place to head the seven teams, with Structures having two leads instead of one. These leads would hold team meetings, give tasks out to their members, and organize and coordinate the work done within their group. At the higher level, they would constantly communicate with each other and with the catalysts to determine the most pressing tasks to be done in order to move forward. The leads set timelines for their teams based on this information, and took full responsibility for meeting each and every deadline. The project had two catalysts whose job was to lead the team, fix problems that created or would create issues for the team, and be the group's representatives. General members were required to take and complete a task weekly, which is a different baseline than just pure attendance and passive participation. This structure, which allowed numerous flexibilities and ultimately drove the group’s members to be individually responsible for their participation, hinged too heavily on the leads being fully committed and passionate as well as the catalysts’ guidance and leadership.

Resources

To help realize its objectives, the project sought out and was provided with various resources for the academic year. These resources included access to the College of Engineering student projects lab (LB-133), which served as a workspace for Electrical and Structures and contained a locker to secure the 3D printer and laser cutter. Because the endeavor was through a special program, it also had access to that program's private computers, conference rooms and classrooms. The project was provided with $7500 in funding from IGNITE and an additional $2000 from the previously mentioned special program. Lastly, students had access to professors with computer, electrical and mechanical engineering backgrounds.

Timeline

At the start of the project, the objective was to have the design of the machine completed by the first semester, and a working prototype done by the second. A full semester of design was chosen to allow for the development of the infrastructure and direction of the project, as well as for iterations of the blueprints to be reviewed and revised. The materials for the machine were to be ordered over winter break, and then assembly was to begin once classes resumed. It was expected that the testing and debugging of the parts was going to take at least a couple months, so most of the Spring semester was set aside specifically for that process.

However, the project's actual timeline varied from the one described above. The design and review process extended into the second semester, parts were not ordered until after winter break, and due to circumstances that will be talked about more in the "Setbacks and Challenges" section, the prototype was not started until a month before the end of the term. Regardless of this change of plans, a great deal of work was done by the leadership and under the individual teams to reach the semblance of a final product. Although the full prototype was not assembled, the majority of the components were finished and ready for construction by the end of the academic year.

Team Description

Computer-Aided Design (CAD)

The CAD team was created to provide all of the computer aided design functions that the project would need over its existence. This ranged from modeling different designs for the 3D-Printer setup to testing and optimizing the print quality of the group's printer.

Electrical/Structures

The Electrical and Structures teams handled the design and production of the 3D Printing vending machine. Mostly, this consisted of constructing a housing unit for the printer and effective means to store printed items. The Structures team and the Electrical team worked closely together to design and construct the structural and electrical layout of the vending machine.

Logistics

The Logistics team was created to manage the cooperation between different teams of the project as well as to write the final IGNITE report. The team created forms and trackers to record the progress of the project and its members and to facilitate interactions within the team and with outside sources.

Research

The Research team was created to conduct research on subjects important to the project, such as necessary materials, components, and potential problems that other teams may face. Another focus of the Research team was to create a "Leadership Codex" that compiled and outlined different aspects of leadership within the project and insight from many of the project members.

Standards

The Standards team was created to test the 3D Printer quality and the Laser Cutter and optimize performance. Additionally, the team took on research and observations about upkeep and the degradation of the machines and possible ways to better maintain the machines and prevent overuse damage.

Software

The Software team's purpose was to create an application that the vending machine would run and explore the possibility of a website portal to said application. The team split up into three sub-groups: the Graphical User Interface team, the Database team, and the Back End team. They also created a fourth subteam for close cooperation with the Electrical team towards the end of the second semester.

Catalysts

The principal investigators (PI's) formed a small group called Catalysts whose main purpose was logistical support for the project as a whole, emotional support for the team, and the instigation of leadership within the project. They were responsible for the entirety of the project, getting to know each member personally, and working to foster a healthy project environment.

Results

Computer-Aided Design

At the start of the first semester, the majority of those who would be joining the Computer Aided Design (CAD) team were freshman with little or no experience with CATIA. Since it would be the main tool used by the team, members had to become familiar with the skill. Since the demand on the CAD subgroup was minimal during these first few weeks when Structures were brainstorming ideas for the 3D vending machine cases, it was decided that there would be a few introductory courses in CATIA for members. Working with the Standards lead and supervised by a professor, students were taught basic computer modelling techniques.

After the few weeks of training were finished, the subgroups started to focus on more specific topics. There were two main areas to look at, Computer Aided Design and Drafting (CADD) and Computer Aided Manufacturing (CAM). Two members took leadership positions and led these subgroups. From there, members working on CADD created and designed project trinkets that could be printed for anyone interested. Others worked on designing a case to secure the 3D printer. Meanwhile, those working on CAM were beginning to research other steps necessary to print something from CAD. This involved converting the file to .stl, then converting that to G-code, which could be read by the printer's software. The main focus was on the G-code conversion software since this aspect influenced optimizations to the printer including improved print speed and print quality. After several weeks, the parent organization requested the CAD team to design awards for the Tomoka Elementary water bottle rocket competition. Members were then assigned tasks to design the medals and trophies which matched the specifications given. CAM, in the meantime, worked on familiarizing themselves with the M2 Makergear 3D printer to gain more hands-on experience.

After the completed models were submitted, the teams shifted focus towards research and optimizing the M2 Makergear 3D printer. CADD began designing a basic model that would determine the print qualities of the various printer settings. Meanwhile, CAM researched the G-Code slicing settings for the M2 in order to optimize print quality. The sub-team leads, two freshmen, also wrote an abstract about this research. After further testing and research, it was discovered that the printer's default settings were already highly optimized and any changes made would only provide a negligible increase in performance. Towards the end of the semester, the team transferred the Structures team's hand-drawn drafts of the 3D printer casing into CATIA.

The start of the second semester was tasked with working on two jobs requested from the structures team: to create a more detailed model of the MakerGear M2 3D Printer and to use the CATIA model of the vending machine case to design an access hatch and shelf for the printer to operate on in order to have easy accessibility. Working on the former of the two tasks were two members, who took measurements of the printer and then recreate it in CATIA, due to it being a single part for design purposes. The later of the two tasks was completed by several members, who each worked on their own ideas concerning how to design the shelf and where to place it. After, they were given the task of looking into drawer slides and the supporting infrastructure. Due to the minimal load on CAD, additional time was given to those working on each tasks in order to better ensure a more polished and refined final version of the designs and model.

Following the completion of these two tasks, CAD waited for the additional parts that Structures needed to be delivered and cut for use in the assembly. During this time, additional sources were looked at, mainly within the parent organization and low priority tasks within the project, in order to generate tasks. One of these tasks was assisting the parent organization with an additive manufacturing based fundraiser. Models for various trinkets were developed in CATIA and then converted into the printable format of G-code.

After the parts were delivered and cut by Structures, CAD measured the structural bars in order to recreate the framework of the casing using an assembly of the cut 80/20 T-slotted aluminum bars. At the time, two members created the outer printer casing frame and the storage carousel frame respectively in CATIA. Afterwards, the Structures team requested assistance in designing a piece to secure the motor axle to the storage carousel in order for it to rotate properly. Through the manipulation of the storage carousel frame assembly, this was created in accordance with the visualization of what structures had brainstormed. Simultaneously, Research requested a shadowbox to be printed to house a physical copy of the leadership codex.

Electrical

During the first semester, Electrical was predominately a part of the Structures team. The Electrical team met with the Structures team and contributed to their meetings. Throughout the first half of the semester, Electrical helped plan what the machine should be able to do, and then determined what would be required to achieve this. The team decided to make a wheel that spins and scrapes printed parts off the build plate. Towards the second half of the semester, Electrical began to brainstorm which parts were required for the machine. Electrical began to meet separate of Structures in early November. Electrical formed a larger, more complete list of parts required and over the next month researched various options to complete each task. For example, to remove parts from the build plate, hydraulics, pneumatics, motors, and linear actuators were initially considered. Over the next three weeks of research by team members, Electrical learned that a linear actuator would best suit the machine. Electrical did similar research for all parts and had a nearly complete parts list assembled by the end of the first semester. More research was assigned over the winter break.

In addition, soldering training kits were purchased for all of the team members as well as others in the project with a desire to learn how to solder. The subsequent two meetings were dedicated to teaching members how to solder with the training kits. This training also provided team members an attainable goal after a semester consisting of mostly research.

After returning from break, the electrical team met several times to discuss research done about the parts. Over the next month, with the help of the project advisor a parts list was compiled and ordered by the end of February.

The first set of parts ordered was temperature dependent resistors to prevent the vending machine from overheating. Also, a webcam for image recognition was ordered to determine if a container was empty or not, as well as which container it was. The resistors were made into a simple circuit and then both parts were handed over to programming for experimenting with.

As parts began to come in after spring break, the electrical team met once to twice a week to put everything together. First, wires were run from the power supply to the linear actuator and the motor controller, and then from the motor controller to the motor. A problem was discovered as a liaison from the Programming team began meeting with the Electrical team lead to discuss how to be able to control all of the various components. The motor bought, under the assumption that it was a stepper motor, was not. While this problem was not rectified before finals began, several solutions were proposed. These included using sensors (Hall Effect sensors, rotational sensors and image recognition) to determine the wheel's position and buying an actual stepper motor. Should the project continue into next year, this issue is of high priority to address.

Once the preliminary wiring was completed, an old soldering iron was scrapped to use its cord to plug the power supply into the wall. Once this was complete, it was possible to make the linear actuator extend and retract. In addition, it was possible to make the motor spin both with and without the motor controller in the middle. The motor speed could be manually controlled on the motor controller by a 5kΩ variable resistor.

The next challenge was to determine how to control these components (the motor, linear actuator, and electronic lock). The Electrical team once again consulted its staff advisor, who provided two circuits to control the linear actuator and the magnetic lock. A 5kΩ digital potentiometer was ordered to connect the Arduino to the motor controller. With the two small circuits constructed, both the linear actuator and the magnetic lock were able to be connected to the Arduino and successfully controlled from it. The digital potentiometer did not arrive in time to assemble that circuit, but it would be a fairly simple matter to hook it up.

Overall, the goals of electrical were not fully realized. The basic goals of connecting the motor, linear actuator, and electronic lock were almost met. Had the last part come in on time, the basic goals would have been met. However, all team members gained valuable experience in constructing electrical layouts for machines, and in soldering wires and reading technical documents. While the physical goals were not fully realized, the personal goals were, as each team member grew from being a part of the project and this team.

Logistics

Logistics team was the only group with a lead who was chosen late into the summer. For this reason there was little work done prior to the official start of the project in the fall. Logistics was primarily concerned with creating structures and forms to facilitate the project while, secondarily, creating PR items for the project. Their primary contributions during the first semester were: organization of the drive, creation of the meeting summary document, the publishing of the Bi-Weekly report, and presenting on behalf of the project to various groups.

In the initial weeks, the group generated half a dozen forms for various functions within the project structure. The documents helped track attendance, summarize meetings, compare progress, and provide structure for the report. These documents were typically assigned out to one or two project participants and discussed within the group for defining characteristics. After insuring the vital information would find its way on to the form the lead let the students have holistic responsibility. These documents although very useful for their individual purposes created a problem for the rest of the project members. The sudden wave of new forms to fill out and inflation of the drive as all the teams began to generate content left many of the forms unused.

A large portion of the first semester was devoted to finding ways to get the necessary information recorded by the general populace. The logistics team made a general calendar for the timeline and checkpoints, a team liaison program was trialed so the forms were filled out, and general meetings were partially devoted to discussing this issue and potential solutions. Eventually it was suggested that the logistic team reduce the forms, reorganize the google drive, and generally make the forms more ergonomic. Instead of excel documents for people to plug data into they created forms which did it for them. Instead of a group calendar they sent out what they absolutely needed to in email form. While this happened the bi-weekly report continued as planned and the group presented to its parent organization. The project was also approached by a school journalist and a presentation was given.

The spring semester began with reviewing logistics' performance in the previous semester and compiling solutions to areas that needed improvement based on poll results collected last semester. This included reorganizing the Google drive structure by ensuring files were stored in proper folders and placing the most frequently used forms on the front page for easy access to members. The next bi-weekly report was continued and released and members began to focus on guidelines and planning for the IGNITE report.

A speech workshop for the Logistics team was organized with the aid of a professor. The workshop was intended to make Logistics members more comfortable with public speaking and oral presentations, as well as provide adequate preparation for the group's second presentation to the parent organization.

Flyers promoting a laser cutting and printing fundraiser were also made and an event was posted on Connection. The remainder of the semester was spent writing and gathering accounts from each team lead to compile into the final Ignite report.

Research

Initially for the first semester, the primary goal of the Research team was to take simple, but time-consuming, research tasks from the other groups. Also, Structures, Electrical and CAD reached out to Research to delegate so that more work could get done in a time efficient and member rich manner. However, this system did not last long because it was soon realized that there was just enough research tasks to distribute within the other individual teams themselves. Consequently, the primary focus of Research became creating a Leadership Codex which would be a record of the lessons learned by the members of the project with regards to infrastructure, methodology, and the direction of the project. Over the course of the fall semester the objectives and content of the Codex were formulated, and many of the initial pages like the Introduction and Project Goals were written and edited. This information was used to track the changes within the project over the course of year and served as an initial evaluation and predictor of the project's success. The work done during this semester paved the way for the Codex to fully develop in the spring.

At the end of last semester, the research team began working on the Leadership Codex – a documentation of the project. Written from the perspective of different students involved in the project, the codex encompassed a wide variety of topics within the project itself. These included the effectiveness of the project structure, the formation and evolution of the overall goals, and the content and organization of the general meetings. At the beginning of this semester, the team put together a list of article topics that would thoroughly document the state and progress of the project. Once the articles were established, the Research team set out to write them. Each week, team members would take an article to write or have others write. The goal was to then have the articles done by the next week so they may each be edited. This process carried on for the majority of the semester until there were about 3 weeks left. From that point on, the main focus of the group was putting the codex in order and ensuring all formatting was correct. It was then time to design the outer cover and create a housing unit for the physical copy. The final product was then presented to several project supporters. An online copy was also made available to future researchers to review and contribute to, turning it into a live document.

Software/ Programming

At the beginning of the project, the goal of the Programming team was to educate its members on programming in Java while planning and researching how to solve the problem of automating a 3D-printer. When the semester started, the team meetings consisted of a lecture by the team lead on basic java programming, group discussion on how to solve future coding problems using software engineering practices. The team members were then assigned a task due the following week to reinforce understanding of the Java lessons each week. The software engineering practices that the team learned and implemented were the creation of a requirements list, development of algorithms and pseudocode, and identifying program structure. The requirements list allowed the team to identify all the aspects of the final product and helped in the creation of pseudo-code and actual code by providing a guideline of pending tasks. The algorithms and pseudocode helped the team start to think like problem solvers and identify, in English, the steps required to address all of the requirements in the final code. Identifying the program structure early on also helped with the development of pseudo-code and actual code by giving the team an idea of how all of the separate pieces would have to communicate in the end.

After two months, the team agreed that the Java lessons took up a large portion of time in the general meetings and that the members should study on their own. Instead, team meeting times were dedicated to team discussion and brainstorming about the project. The team then agreed to split into three groups to more efficiently work on planning. The three sub-teams were each in charge of planning their piece of the final code to begin coding it during the second semester. The three areas of focus were the user interface (UI), the back-end programming, and the external database. By the end of the semester, the UI team and the back-end programming team had detailed program designs and pseudo-code while the database team had a locally run database with image files that would be expanded on during the second semester.

Standards

The Standards team began the fall semester pursuing, at the direction of the catalysts, a standard by which all 3-D printers could be compared. Preliminary research did not reveal that there was an existing standard; however, further research revealed several free and pay ware products that had the potential to fill this role, including 3-D Benchy and CTRLV.

Since there was already significant research conducted on 3-D printer standards, the Standards team's focus shifted to research the effects of long-term wear and tear on a 3D printer's reliability and accuracy. Since the project was printing at a high volume and the data on reliability would be useful to the team as a whole, further research was conducted. This research was focused initially on peer reviewed, academic sources. This research yielded little to no information so, using 3-D Benchy, the Standards team created several baseline prints that were to be compared to future prints, in order to track the MakerGear's accuracy. Additionally, a recording table was created for the members directly involved in printing to record all print failures. This data would be useful in determining the amount of required maintenance for an autonomous 3-D printer.

Unfortunately, several months of data recording and printing one 3-D Benchy test per month did not yield any usable or statistically significant trends. In the second semester, Standards acquired the responsibility for repairing a broken laser cutter, which was to be used by the

Structures group to cut parts for the final machine. The Standards team's efforts to repair the laser cutter were cut short by political issues between the involved groups. Following the laser cutter project, the Standards team was disbanded.

Structures

Before research began on the design of the vending machine, students examined maintenance requirements and error prevention for both a 3D printer and vending machine. Some of the requirements and error prevention techniques that were analyzed further included maintaining a constant power source, surge protection for the printer, printer build volume restraints, safe retrieval of vending machine items, replenishment of product, and heating and cooling. Research on these specific topics was conducted in groups. During the project's weekly meetings, these research topics would be brought up as tasks that needed to be understood by the following meeting in order to improve the group's familiarity with the processes of both a 3D printer and vending machine. The eagerness of the team enabled topics to be easily assigned since students would readily volunteer to research topics that interested them. At the following meeting, the students would briefly present the topic that they covered in order to reaffirm their understanding of the material and convey it to others. This research became the foothold that allowed the team to begin to gain a fundamental understanding of 3D printing and vending machines leading to the purchase of key mechanical components.

The students formed small groups to make rough sketches of the designs they wanted to test. After analyzing each of the different possible designs, the solutions to go forward with were decided on based on plausibility and how well they would integrate with one another for the final design. The design included a linear actuator with an attached ramp to remove the finished print from the printer and a storage carousel to hold prints prior to removal. During the process of integration, the team discovered that focusing on mechanisms that would lower regular maintenance are more efficient than complete automation.

The design went through a product design review, using CAD to help those at the review visualize the design. Mostly positive feedback was received on the design, there were a few additional aspects of it that others wanted to see implemented in the physical prototype. This meant adding a maintenance drawer to access the printer, making the casing more aesthetically pleasing, and starting to put real numbers behind measurements for both part sizes and power to the electrical components.

For Structures, most of the second semester was spent trying to find someone to cut the structural material for the team. Either the team's liaison to the machine shop in the Lehman building, or the person tasked with talking to the liaison was not doing as asked. Thus, the team as a whole spent a majority of the time twiddling their thumbs. Approximately halfway through the semester, a new liaison to a different machine shop was found. A student in Formula SAE was gracious enough to volunteer his time to cut parts in the M building. Two weeks went by as the team recounted what items were, and still needed to be, measured. During those two weeks, the team also put together the crudely cut walls of the inner carousel from the previous semester.

After the material was cut, the team spent about two more weeks putting the parts together. Near the end, the team realized that a few more structural bars would still be needed. Additionally, two items from the original design were still missing. Once the structure was put together, a few problems with the integrity were noticed. The team went back to the drawing board immediately to design what else would be needed to construct the vending machine.

Unfortunately, the team was out of material to cut as well as nuts, bolts, and brackets to hold it together. All of these parts were ordered, but by the time they came in, the semester was too close to an end to accomplish much. Most, but not all, of the bars were measured out in the hopes of being cut this semester. With only two weeks of the school year left, being able to coordinate with the team's liaison to the machine shop would be near impossible, let alone finding the time to integrate the newly cut metal with the rest of the structure.

Discussion

Despite failing to produce a finished vending machine, the team had done valuable work by the end of the second semester. The printer was run for 24 hours non-stop for a week on two separate occasions, proving that a consumer-grade printer could be used in this type of product. A .stl file was created with the vending machine's exoskeleton, designed by the structures team. This skeleton was built, but the internal framework and electronics were never applied due to time constraints. Code was written for the printer to accept a file and prep it for printing, however because this part of the assembly was not reached it was never tested. Electrical had hardwired some of the components, specifically the actuator and the hinged door panel. A Leadership Codex was written and is currently being compiled for use in the fall semester.

The stated goal for the end of the second semester of this project was a functional prototype. Although that goal was never met, significant strides were made and it truly came down to a time constraint that stopped all of the pieces from coming together. Various skills were learned, honed, and implemented during this process, including: CATIA, Java, Python, soldering, electrical design, engineering calculations, team organization, project management, public speaking, problem solving, product design, and team building. Each of these hard and soft skills will be potentially very useful in future projects and careers. Through feedback surveys conducted by the Catalysts throughout the year it was clear that participants greatly enjoyed the project and attribute it to personal growth in time management, technical skills, leadership, and communication.

As was stated before, the project's secondary goal was to challenge people to grow personally and professionally. Although it fell short in producing a working machine, it made a great effort to achieve this other objective. Hopefully the results will be apparent in its participants.

Conclusion

The group took on some lofty goals. Its primary objective was to create a device equivalent to that of graduate-level work. The hope was to leverage greater numbers to make this device a reality. However, those 45 students were going to have their own logistical cost, the project structure was going to have to flex to handle them all, and individual tasks would have to be minimized to ensure everyone's participation. The team ended with 28 members at the last meeting who had all participated for the majority of the project's span. This student body was incredibly rewarding to lead and work alongside.

The project's outputs fell short of what was desired but the challenges faced were diverse and rewarding to overcome when possible. The group experienced leadership changes from day one all the way up to the end of the first semester. It had new people joining and old people leaving every week. Objectives were both added and removed as teams changed focus, approach, or style. It was exhilarating to watch the leads get more vocal, the once quiet freshmen start suggesting and implementing changes, and the leaders of the group start growing in both quantity and quality.

Although no prototype was created, the work done was highly interesting, technical, and important in ensuring a successful future for this project. The ability to implement functional code was an invaluable experience for a student. Getting a circuit design to work and manipulating it with an arduino was a highlight for many. Designing, cutting and putting together something as seemingly boring as a metal frame was unimaginably amazing. Given more time these pieces would have come together. One more month, free of finals and structural changes in the parent organization, would have seen the code finished, the inner structure prototype completed, the electrical components attached and perhaps a fully autonomous print, albeit without the bells and whistles of a finished product.

As of June 2016 there are plans to have a smaller team return in the fall to redesign, finish the prototype, and potentially patent the product. It is that team's belief that this idea has some weight and intrinsic value that they hope to capture. If this group is kept together and passionate about this project, there is great hope that they will deliver on it in the near future. The team thanks both IGNITE Research and the assisting program for their generosity and help in making this endeavor possible. In the future we intend to disappoint less and enthrall even more.