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Interdisciplinary Senior Design Project to Develop a Teaching Tool: Dragon Conductive 3D Printer

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Abstract

The desired current set of skills required of modern engineers and technologists has been steadily expanding. In addition to familiarity with manual machining and prototyping techniques, mastering CAD/CAM, Computer Numerical Control (CNC), and automation methods are increasingly becoming essential tools in the design, prototyping and manufacturing of complex systems. In this paper, an inter-disciplinary design project towards the development of a 3D printer machine is presented as an alternative to purchasing and installing traditional prototyping equipment to provide hands on experience. The Dragon 3D printer is designed to bridge the gap between commercial printers and consumer 3D printers – to be the first "prosumer" 3D printer. However, the Dragon printer is more than just an upgraded Makerbot – it has features that are not available even on commercial models. The Dragon printer has evolved into a commercial printer with never before seen features - for a fraction of the cost, and perhaps most interestingly, at a fraction of the cost to run as other commercial models. The most exciting feature of the Dragon conductive 3D printer is its ability to create 3D prints with integrated traces and variable resistivity. This will take 3D printing from making solid objects to making useful electronic devices. The Dragon 3D printer will be useful for engineering technology classes – because it continues the trend of technology being more powerful, more hands on, and available for a fraction of the cost of other alternatives. The Dragon 3D printer will make prototyping viable for larger parts – in a way that was not possible with smaller printers and expensive filament. The Dragon 3D printer will be a boon to students, prototypes, and hobbyists interested in the exciting field of rapid prototyping.

The significance of the methodology to be applied in this capstone course project is to **combine theory and practice to prepare the students to become better problem solvers and obtain practical solutions to real life/simulated problems using a project based approach.** Students in the Mechanical, Electrical, and Industrial fields along with many others can learn many new skills from multi-disciplinary projects such as the design and development of a 3D printer. Such projects show students how to use different types of technology, and demonstrate how advanced technology can be used in an innovative application. Overall, many different fields of engineering can benefit from this application, enabling the development of skill and knowledge in many different engineering aspects and processes. This capstone design project stimulates the students' interest in real-world product realization. As manufacturing laboratories are very expensive to develop, this project can also be adapted at other institutions that have limited funding to improve manufacturing process and prototyping facilities.

Background

In our Engineering Technology program , many courses related to robotics, design, and materials are offered to students. Courses such as Robotics and Mechatronics, Quality Control, Manufacturing Materials, Microcontrollers, and Applied Mechanics can benefit from the laboratory experience in applications of mechatronics, robotics, and rapid prototyping. As well as helping in the teaching of various courses, such experience benefits students who are pursuing degrees in the engineering field. Students in the Mechanical, Electrical, Industrial and Biomedical fields along with many others can learn many new skills from multi-disciplinary projects such as designing and fabricating a desktop 3D printer machine. Such projects show students how to use different types of technology, and demonstrate how advanced technology can be used in an actual application. This project instills future engineers and technologists with various advanced skills that can be used in their careers. Overall, many different fields of engineering can benefit from this application, enabling the development of skill and knowledge in many different engineering aspects and processes.

Students in the Engineering Technology programs are required to complete a yearlong three series of capstone course MET 42X Senior Design. This three quarter course sequence aims to train the students in identifying projects of relevance to the society, in planning and scheduling a solution, and in entrepreneurial activities that may result from the project. The course is worth three credit hours per quarter offering. The course is also intended to cover an industrial project starting from the proposal writing and conceptual design to final prototype building and concept realization steps. The course is focused on proposal and project progress report writing, prototype fabrication as well as design improvement and optimization. Each quarter, student teams must submit a progress report and demonstrate a physical working prototype at the end of academic year. During fall and spring quarters, they conduct an oral presentation to faculty and practicing engineers from industry. Since this is a capstone project course, many ABET Student Outcomes are assessed each quarter as indicated in Table 1. Written, oral and student contribution rubrics were developed specifically for the capstone project course and are used during assessment and evaluation. Assessor body include Engineering Technology program faculty, sponsoring company engineers and invited Drexel University faculty.

Table 1. ABET Students Outcomes assessed per quarter offering.

ET COURSES		**OUTCOME(s)**
MET 421	Project Design I	**a-k**
MET 422	Project Design II	**a-h, j, k**
MET 423	Project Design III	**a-h, j, k**

Problem Description

Since purchasing and installing rapid prototyping equipment is not an option for every campus of Drexel University or similar engineering schools, an alternative solution to providing hands on experience with rapid prototyping equipment is desirable. Less than a year ago Harvard Business Review declared, "3-D Printing Will Change the World"[1]. President Barack Obama pointed to 3D printing as a technology "…that has the potential to revolutionize the way we make almost everything"[2]. It is believed that 3D printing is a technology that will democratize manufacturing - making it possible for everyone to bring their dreams to life in a physical object. 3D Printing will increase productivity - while simultaneously helping the environment and manufacturer's bottom line by reducing material waste. A prototyping machine with a desktop form factor which would be easily transported between campuses would eliminate the need for multiple prototyping machines and would improve the quality of several courses including

EET102-introduction to technology, MET407-manufacturing processes and capstone senior design (MET42X sequence) courses by providing more hands-on lab experiences, accessibility and reduced operating costs. The proposed 3D printer brings a new twist to the field of 3D printing - conductivity. The student design team has four student members. Each student brings different strengths to the table. One of the students in the team is studying dual concentration (electrical and mechanical engineering technology), one is electrical and remaining two is studying mechanical engineering technology. They wanted to be able to 3D print not just a vase or a plastic toy – but useful electronic devices such as a flashlight, a flexible sensor, maybe even PCB boards. As interesting and novel as this idea is, the design team did not merely want to create a typical 3D printer that could also print conductive parts. They proposed to make something fundamentally better – a machine that addressed some of the deficiencies of today's 3D printers.

The proposed desktop rapid prototyping machine would fit on a standard desktop or table, would interface with commonly available open source prototyping software, would be powered by a standard AC outlet, would be easy to use and robust enough for educational use, and would not be cost prohibitive to operate.

Existing Products and Target Market Research

Currently the vast majority of 3D printers priced under $10,000 print with one print head – deluxe models often offer two print heads[3]. They do not include a mechanism to eliminate fumes. They typically range from $300 to $3000 with a build envelope typically from 100 mm^3 to 300 mm[3, 4]. Virtually all of the printers currently available use belting for motion control – although at least one 3D printer offers lead screws on one axis.[5]

Recently, one of the first surveys of 3D printer users was published and the findings suggest several key issues with the current state of 3D printers. When asked to select their most desired improvements to 3D printing, respondents chose - in order of preference: object quality, cheaper material prices, speed, a cheaper 3D printer price, and metal printing etc.[6]

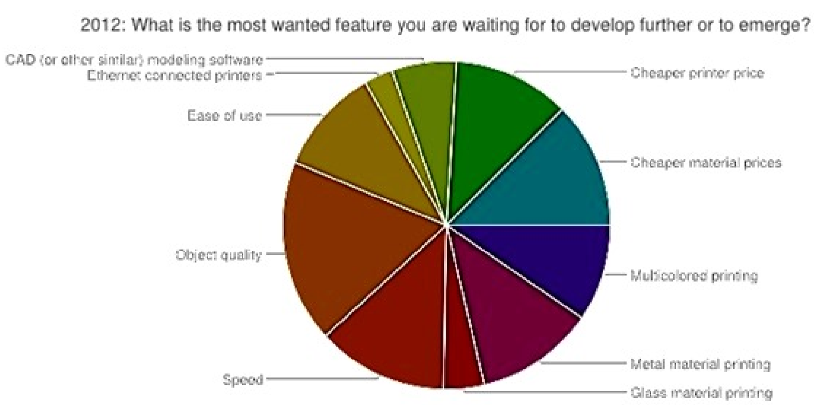


Figure 2. Users top choice for improvement to 3D printers.[7]

Many new 3D printers have been developed that address user's desire for a low cost 3D printer. Recently a $100 3D printer was released[8]. However, a lower cost was not the most requested feature by 3D printer users. Most users want a higher quality machine that runs faster, does not cost as much to run, and comes with new choices for printed materials. Only 11.5% of 3D printer users surveyed listed a lower cost as their top desired improvement[6]. The market has not yet provided these features, possibly because the 3D printer market has been divided sharply into two segments, each of which produce two very different types of printers. The market is segmented into inexpensive open source 3D printers e.g. peach printer, RepRaps, Robo 3D etc. and the professional machines from Stratasys Inc., Projet, and others. The price range between these market segments leaves a very wide gap. The consumer 3D printers typically range from $300 - $2750 while a professional machine ranges from $10,000 – $380,000[9]. Although 3D printer users want a higher quality printer – professional quality options are virtually non-existent for under $10,000. Obviously there is a gap, to borrow a term from the camera industry, for a *prosumer* 3D printer. A prosumer printer would attempt to address the quality issues of desktop 3D printing instead of merely lowering the price.

Patent Search

The recent boom in 3D printing market is a consequence of the expiration of a large number of patents relating to Fused Deposition Modeling (FDM®/FFF) 3D printing which occurred a few years ago[10]. In February 2013 another slew of patents related to selective laser sintering (SLS) printing are set to expire and we may see another burst of development in the field[11]. However, many key features are still under patent and will continue to hamper development and consumer options for the foreseeable future[12]. One of the key patents hampering the development of a quality and inexpensive FDM®/FFF printer is U.S. Patent US 6722872 B1 *High temperature modeling apparatus*. (US Patent No. 6722872 B1, 2004). The patent protects the idea of running a Cartesian gantry outside of a heated chamber (Various, 2012). This patent is crucial to printing large objects with FDM®/FFF techniques because if the plastic is not kept at a uniform temperature, then the temperature gradient will lead to warped parts. This patent is the reason that there are only a few 3D printers available under $10,000 with a build envelope larger than 300 mm^3. Although recently a delta style 3D printer was designed with a heated chamber as the delta style gantry keeps it from infringing on the patent[13].

Concept Generation, QFD - Quality Function Deployment Analysis and, Product Development

The student design team proposed a desktop prototyping machine that met a number of requirements to be considered acceptable for use as a teaching aid for the ET courses stated earlier. Some of these requirements placed additional constraints on the design which may limit its functionality and usefulness (Figure 2). Students used QFD analysis to determine what features are most critical for their design. This analysis showed them the importance of quality components, ball screws, and aluminum framing in the design. From personal experiences with 3D printers, and from the target market research, design quality needed to be a major focus of the machine design. With that in mind the students were able to use QFD analysis to arrive at some specific product specifications.

Ketos - Pellet to Filament System

To develop a desktop machine to produce low-resistivity 3D printer filament led to the development of the Ketos – Pellet to Filament System. There are currently two major filament extruders systems on the market, the Filabot and the Filistruder. While both filament extruders can produce 3D printer filament from pellets, they cannot mix in additives like carbon powder. The students took inspiration from the original filament extrusion system, that both the Filabot and the Filistruder are based on - the Lyman open source design filament extruder. Design in general, and mechanical design in particular are iterative activities. Iteration, looping back to explore alternatives, is an essential part of the design process[14, 15]. Iterating is, of course, time consuming and costly, but a systematic search for creative solutions early on in the product development process is not, either extremely costly or terribly time consuming and is fundamental to the design of innovative products.

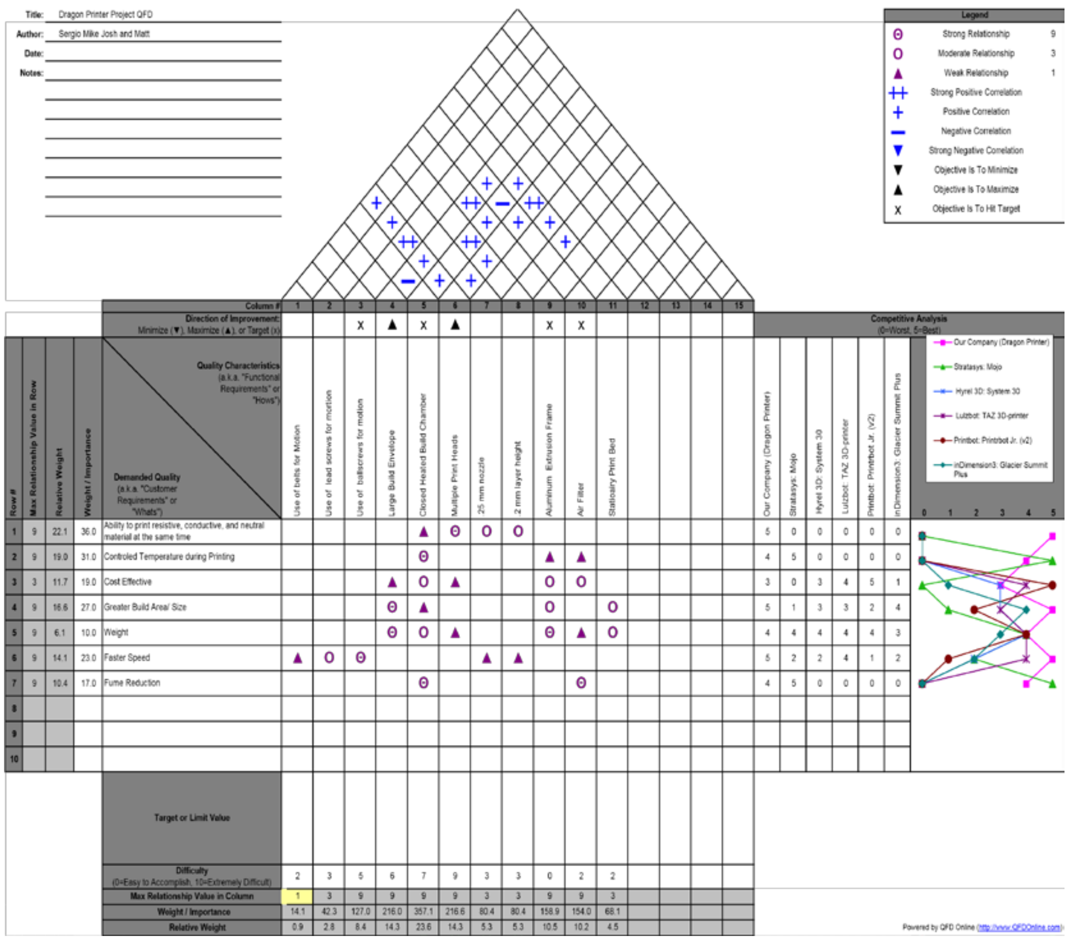
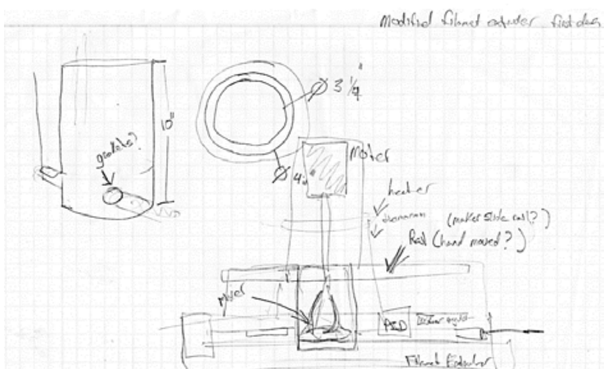


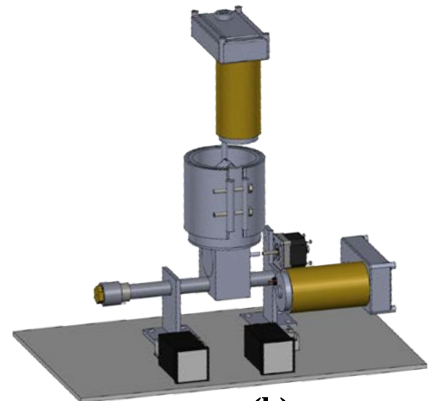
Figure 2. Quality Function Deployment diagram for the 3D printer design.

Therefore, in this project, the students learned what engineers have to deal with and how to look at a problem and taking the steps to fix it. They underwent several design iterations, going from rough sketches as illustrated below in Figure 3, to a functional design for simple extrusion system, to a design capable of mixing in different additives.

The conceptual design, shown in Figure 3b will use various additives with plastic pellets, such as pigments, carbon powder, or fibers, etc. It will also allow a user to recycle 3D printer parts, by melting them, and extruding the plastic as 3D filament. Printing with conductive plastic made it imperative that there would be a minimum of four print heads on the 3D printer. Head number one is dedicated to print a very strong ABS plastic material. The second print head would print with a dissolvable support material –such as polyvinyl alcohol, a plastic that is dissolvable in water.



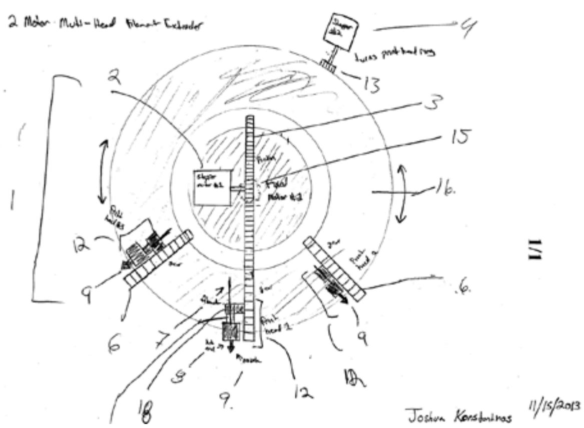
(a)



(b)

Figure 3. (a) Concept Sketch of the Ketos Pellet to Filament System (b) SolidWorks® rendering of Ketos Filament Extrusion System

Two additional print heads are also needed - one to print conductive plastic and another to print a slightly more resistive plastic so that resistors can be printed. The design team developed a novel two-motor multi-head system – currently patent pending – that will allow controlling a number of print heads with only two motors (US Patent No. 61/904,868, 2013 - Patent Pending).



(a)

(b)

Figure 4. (a) Two-Motor Multi-Head Print Head Assembly (US Patent No. 61/904,868, 2013 - Patent Pending) (b) SolidWorks® Photo Realistic Model of Dragon 3D Printer Frame

This design will allow creating a multi-head 3D printer without the costly custom board circuitry development – and without losing valuable x-axis space as in traditional multi-head systems. It also reduces the cost for multiple motors. For the frame of the machine, aluminum was the choice of material. Aluminum extrusions offer quick assembly for the prototype as well as the ability to easily increase the size of the printer based on the custom needs of the end user. Similarly, with the gantry frame design, the highest quality parts available were selected to be able to print circuits effectively. It was therefore an easy decision to use ball screws as opposed to cheaper belt drives. To realize the full potential of conductive 3D printing, the design team needed to create a very high precision machine. For this reason, balls crews, all metal framing, and other high quality components are used.

Democratization of Manufacturing

3D printing has many social and environmental benefits over traditional techniques. 3D printing democratizes manufacturing – making it possible to create a product without needing to create 10,000 units in order to be cost-effective. This will allow not only greater productivity, more entrepreneurship opportunities, and easier prototyping, but it engages more people in the design process of the things they use every day. Furthermore, 3D printing promises to allow for mass customization - giving consumers access to products designed specifically for them. Already 3D printed glasses are being sold that are designed and manufactured for each individual.[16]

Environmental Benefits

Recently research was done on the environmental benefits of 3D printing. In this recent study a life cycle analysis of conventional plastic and 3D printer plastic was conducted. According to this research "the results indicate that the cumulative energy demand of manufacturing polymer products can be reduced by 41–64%" though distributed 3D printing.[17, 18]
The design for the Ketos – Pellet to Plastic system should be even more advantageous for recycling as the heated mixer allows for larger pieces to be melted and extruded with no additional processing. Research has shown that recycling plastic filament can provide embodied energy saving between 69 to 82 %. [17, 18]

Conclusions

This project has expanded considerably since initial proposal prepared by the student design team. The conductivity capability that is added to 3D printing necessitated extensive research into conductive polymer development as well as the design and prototyping of the Ketos extrusion machine. The student team was successfully able to obtain a patent pending solution to the multi material problem[19]. Engineering Technology student design team has produced a solid design and has applied the required engineering expertise to complete and deliver a functional desktop rapid prototyping machine to Drexel University. Prototype building and testing is planned in winter and spring terms to prove that design is feasible and that the electrical and mechanical design selections are appropriate. The economic analysis indicated a decreased material cost trend at higher production volumes and has determined potential selling prices accordingly. Budget projections show that the material cost of the printer will be around

$2,450.00. The Ketos Filament Extruder cost roughly $490.00 in material costs. The prototype cost is on the target and feasible to be duplicated at other teaching institutions.

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