Additive Manufacturing for Custom Design: Process and Evaluation and Cost Management

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Abstract:

Custom devices are challenging in design and manufacturing cost and require more time to be made. Using Additive Manufacturing (AM) proved to be more suitable in reducing the cost and time regardless of the geometric complexity of the part to be made. AM transforms the way some products are made. These aspects made AM gain lots of momentum in the last decade. In this communication, we will show how to introduce students to advanced design concepts using AM and real life scenarios to make custom parts. Most of these custom products will address the challenges of the medical industry which is the largest one in the USA. Students will be exposed to different software packages and different design and fabrication techniques. The goal of this project is to illustrate the future of additive manufacturing technology, how to prepare students to become the future experts in this field, and to provide a model that can be adopted by academic institution. Survey for some of the main activities were conducted and evaluated.

Introduction:

From construction and bioengineering to aerospace and defense, Additive Manufacturing (AM) is revolutionizing manufacturing and has the potential to transform several industries. AM has been called the *Second Industrial Revolution* – Kondor et al., (2013). The revolutionary aspect of AM is not the uniform mass production of the First Industrial Revolution, but mass customization of manufactured devices. AM technology allows a 3D shape to be defined in digital space and to be directly transformed into a tangible object. The transformation by AM is fast and inexpensive compared to most traditional fabrications (Eyers and Dotchev, 2010). Durable, biocompatible plastic resins can be formed into any shape using AM devices. This technology is already impacting healthcare with the production of custom shaped prostheses and implants (Lipson, 2012). Kondor and colleagues (2013) have shown that through AM technology, surgical instruments can be quickly and economically printed in a biocompatible polymer to produce custom surgical instruments tailored to the specific needs of a surgeon. This concept was recently explored by the Defense Advanced Research Projects Agency (DARPA) and the produced instruments were used to successfully complete surgical procedures on a realistic human simulator.

In the medical device industry, the United States remains the largest medical device market in the world with a market size of around $156 billion, and it represented about 40 percent of the global medical device market in 2017. U.S. exports of medical devices in key product categories identified by the Department of Commerce (DOC) exceeded $41 billion in that year[1]. According to the record of the US DOC there are There are more than 6,500 medical device companies in the U.S., mostly small and medium-sized enterprises (SMEs). More than 80 percent of medical device companies have fewer than 50 employees, and many (notably innovative start-up companies) have little or no sales revenue. . Furthermore, there is a continuous need nationwide and worldwide for cheap medical devices especially in developing communities. According to the World Health Organization (WHO) world report on disability in 2011 , About 15% of the world's population lives with some form of disability, of whom 2-4% experience significant difficulties in functioning. The same report states also that 0.5% of the **population** of a developing country have a disability that will require a **prosthesis** or **orthosis** and related rehabilitation services. UNICEF reported that 30% of the street youth are disabled. It is a fact that prosthetic devices' life time is approximately three years and can be much shorter for children.

Given the need in the early years to master theories and principles, a problem has been that it takes some time for students to get to the real-world application. The shift to experiential and student-centered learning is crucial to attract and retain more engineering students. The earlier we expose our students to research and hands on activities, the earlier we break down their barriers, their fears over hardware and software, and the clearer their learning experience is. This learning approach is described by Bain (2004) in *What Best College Teachers Can Do* as an approach that effectively addresses how people learn most effectively:

- They try to move from specific principles (design and fabrication of specific custom devices) to general principles (design, manufacturing, materials,etc.)
- They try to answer questions or solve problems they find interesting, intriguing, or beautiful

[1] Record of the US Dept. of Commerce (www.selectusa.gov/medical)

- They work collaboratively with other learners struggling with the same problem
- They have the opportunity to learn by doing
- They have many opportunities to speculate about possible answers or solutions

Overview:

This approach is designed for students who are entering their second year or semester in mechanical engineering. The approach is a gradual approach where students will be challenged in three different stages. These stages can be classified as follows:

Stage 1: Curriculum Update:
Students will be equipped with the necessary tools to work on AM and custom design. Therefore, an update in different courses at different levels (sophomore, senior, and junior) is made. Tolerance concepts and rules are introduced in Engineering Graphics course (first year), custom design and AM is introduced in Advanced Solid Modeling course (second year), AM processes are introduced in Rapid Prototyping course (third year) and hands-on additive manufacturing is introduced in the Senior Design Project (fourth year). The most critical years are the first and second years. In the first year students have to use the ETI trainer software which helps them learn about tolerance and how to implement it. The software takes them in a tour that continues for 24 – 27 hours of independent work (outside of the classroom) where complete many exercises and quizzes. By the end of the course, the software issues them a GD&T certificate if they manage to pass the certification exam. Many students managed to pass the exam. .

A very good example of advantages of curriculum update is the Advanced Solid Modeling course. In this course students will learn Autodesk Inventor software which is used in 3D modeling. Students will get enough skills from this course to make products using assembly and animations as well as producing working drawings. We have provided in depth details about the update to the manufacturing part of this course in a previous publication [5]. Based on this course students can take the first part of the Autodesk Inventor certification exam. AM is introduced in this class and students get the opportunity to fabricate their own design. Students have to finish a team project for a medical device where they have to design, fabricate, and present the device to the class. The project will take 6-8 weeks to be completed.. Students are introduced to custom devices and specifically custom orthopedic implants. The idea is to design an orthopedic implant that can fit specific patient's anatomy. The student version of Mimics software (Materialise Comp., Belgium) is introduced. The software is easy to learn and emphasizes content knowledge from previous courses such as orthographic views.

The design and development of custom medical implants requires *multi-disciplinary* input and presents many challenges. *The process is based on patient-specific anatomy*. The process of implants starts with a MRI scan - Ma et al., (2013). Figure 1 below shows some of the student work including simple stress analysis that they performed. Figure 2 shows some of the students' project they did in the course.

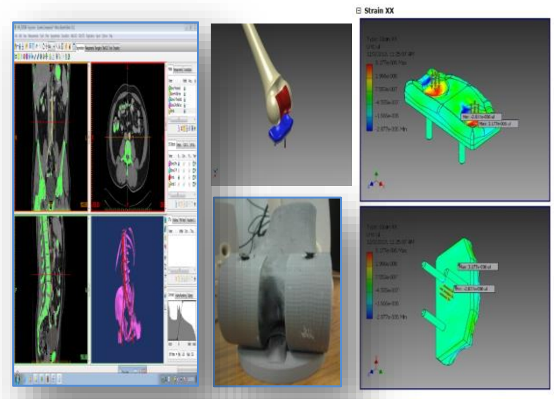

Figure 1: Design and analysis of a custom knee implant

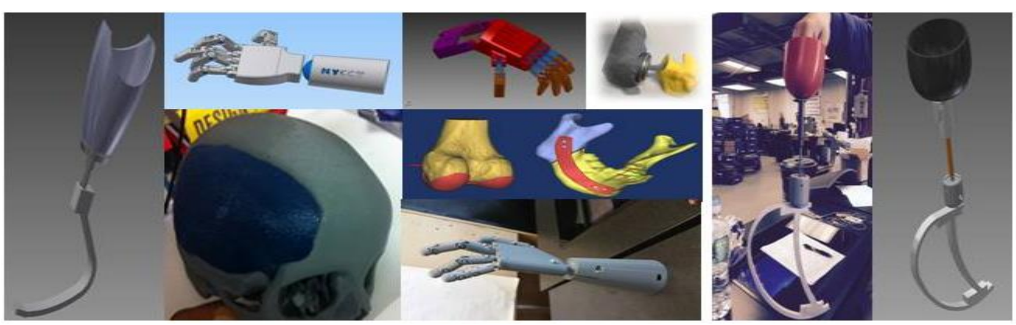

Figure 2: Some of the students' projects in the Advanced Solid Modeling course.

Stage 2: Summer Training Program:
The objective of this training is to provide students with a more in depth experience in AM and design. The training includes:

a. Hands on workshop on how to build a 3D printer: students build, calibrate, and test their own 3D printers. This training lasts for three days.

b. Seminars by faculty and professionals from the industry: The seminars hosted by professors from other universities, scientists from NASA and Hospital for Special Surgery. Dental technicians who make the dental prostheses are invited to present. The seminars include mostly case studies and students have to work together in teams to solve some of the cases and present them by the end of the seminar. Each seminar lasts one or two days.

Stage 3: Working on projects with faculty:
Once students grasp all fundamentals from stages 1 and 2, they are ready to work with professors in a research that involves CAD, AM, and cost analysis. The challenge about medical devices is the price of medical devices. Therefore, students are encouraged to redesign or improve an existing design of a medical device in order to reduce the cost. The prices of these devices is high in the U.S. and they are simply not affordable in developing communities. Therefore, we communicate with organizations in developing countries where such projects will have the greatest impact. However, though it is easy to make parts in AM, large production cost estimates are difficult to calculate. With this in mind, students struggle to find some parameters to minimize their projects' cost. We will present three examples of these types of projects.

A. Reducing the cost of loupes:
The average cost of a loupe, extensively used by medical practitioners, is $300. The task for second year students is to improve the design and reduce the cost. This task made students think in a different way. They have to analyze all details including manufacturing cost, materials, cost-effective design, and mechanical strength. Designing loupes is challenging and requires high skills in modeling. The initial cost estimate is $150 dollars

Figure 3: Loupes designed by students

B. Improving the design and reducing the cost of foot braces.

This project is a response to a request from Cheshire Center for Kids with Disability in Sudan (Africa). The cost of these braces is high and there is a great demand for it. Clubfoot or talipes refers to a congenital deformity of the foot. The foot has a typical appearance of pointing downwards and twisted inwards. The foot braces will help in fixing this deformity. Cheshire Center needs stronger, lighter braces that are safe, and the attached accessories need to be stronger. The price for foot braces ($50 – $100) is considered high for the population in a developing countries such as Sudan. Thus the cost was one of the parameters students have to design for. As a result, materials used had to be changed. Students tried different materials such as carbon fiber for the plate and other accessories where strength is needed. Mark Forged 3D printer was used to create the carbon fiber parts. The distribution of layers of carbon fibers has to be controlled to customize the strength. Different percentages of carbon fiber were tried. Since carbon fiber is expensive, students have to be creative in exploring other options like low-cost polymers with high strength or could be strengthened by heat treatment. Also other composite materials used by the same printer are explored such as Kevlar and fiber glass. The project brings the spirit of challenge having the students working on a problem they find it fun to solve and it impacts the life of children. Figure 4 shows the design and fabrication of the braces as well as the financial cost estimated by the students.

C. The Bionic Hand

The bionic hand is a custom high-cost prosthetic device. The price range for bionic hands is exorbitant, ranging from $3K - $80K.. The project considers a bionic hand for below-the-elbow amputees. The challenge in creating a bionic hand is the balance of creating a low-cost hand while maintaining the complexity of the model where design, fabrication, and mechatronics have to be optimized and integrated. Students were able to design and fabricate the hand; they also attached the sensors and tested the hand. The test is posted online[2]. The fabrication and accessories (servos, motors, sensors, etc) cost came to be less than $300 and varies from team to another.

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[2] https://www.youtube.com/watch?v=Z8-grwxP97w

Item	Quantity	Material	Price
Upper Connected	2	Carbon Fiber	$3.94
Grooved Piece	2	Carbon Fiber	$2.16
Nut Handle	2	PLA	$0.20
Bar (TBD)	1	Carbon Fiber Fiberglass Kevlar	$11.64 $9.80 $11.74
3/8" - 16 Bolt	2	304 Stainless	$0.24
3/8" - 16 Nut	2	304 Stainless	$0.12
			$16.46 - 18.30

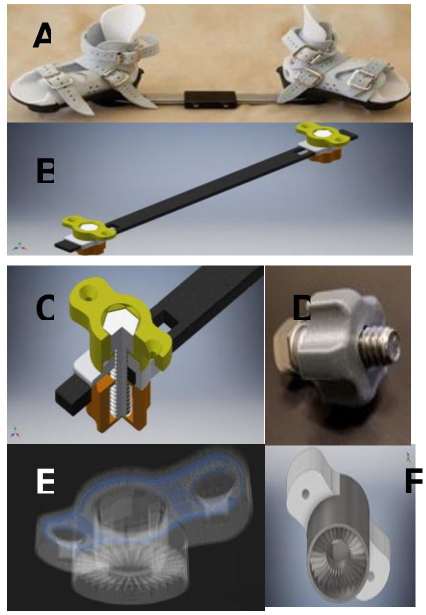

Figure 4: Left: cost estimate of the design using Mark forged 3D printer and regular low cost FDM printers. Right: Foot braces. A: original foot braces; B: a model designed by the students; C & D : Fixtures in the end of the foot braces; E & F: distributing carbon fiber layers on the closing nut of the braces to improve its strength.

Evaluation:

By the end of the year, students' response to this approach was surveyed and evaluated. There was more focus on the workshops presented by faculty and industry personnel as well as team work. The results of the survey are shown in Table 1 below. Students realized the value of collaboration and the industry's needs. Some of the comments received from the students were:

- *"The importance of engineer-surgeon collaboration in the creation of patient specific implants."*
- *"The FDA has approved medical devices that are implanted for dental work at a faster rate than those for limb prosthetics/replacements."*
- *"It is possible to retrieve failed knee/hip implants from patients and perform mechanical testing to improve product design and performance."*

In response to a question about the what was most liked about the workshop, students stated: *"Make it longer; everything; Dental devices; Using the mimics software; The coding problems; The project that was given to us , using our mechanical engineering skills to design; The hands on coding work and learning about bits; The instructor had a mechanical engineering background but was involved in medical devices so his experience was based on an interesting perspective."*

Table 1. Student Feedback about the Workshops

About the Workshop	**Level of Agreement**				
	Strongly disagree	**Disagree**	**Neither agree nor disagree**	**Agree**	**Strongly agree**
The workshop was well organized.	0% (n=0)	3% (n=1)	9% (n=3)	66% (n=23)	23% (n=8)
The presentations were clear and informative.	0% (n=0)	0% (n=0)	11% (n=4)	54% (n=19)	34%(n=12)
The activities were helpful.	0% (n=0)	0% (n=0)	3% (n=1)	69% (n=24)	29%(n=10)
There was adequate time for questions and discussion.	0% (n=0)	6% (n=2)	0% (n=0)	69% (n=24)	26% (n=9)
I learned the information.	0% (n=0)	3% (n=1)	9% (n=3)	60% (n=21)	29% (n=10
The workshop was what I expected.	6% (n=2)	6% (n=2)	9% (n=3)	66% (n=23)	14% (n=5)
I had an opportunity to work with other students.	0% (n=0)	6% (n=2)	11% (n=4)	54% (n=19)	29% (n=10

Additionally, students who worked on projects in small teams were also surveyed. The result of the survey is shown in Table 2 below. One of the important skills students need to master is team work. Thus the survey covered this skill separately due to its importance. This is shown in Table 3.

Table 2. Student Perceptions of the Team Experience

Aspects of the team experience	**Strongly disagree**	**Disagree**	**Neither agree nor disagree**	**Agree**	**Strongly agree**
The team has a meaningful, shared purpose	10% (n=1)	0% (n=0)	20% (n=2)	20% (n=2)	50% (n=5)
Team members clearly understand their roles.	10% (n=1)	0% (n=0)	20% (n=2)	20% (n=2)	50% (n=5)
Team members take personal responsibility for the effectiveness of the team.	10% (n=1)	10% (n=1)	10% (n=1)	10% (n=1)	60% (n=6)
Team members address and resolve issues quickly	10% (n=1)	0% (n=0)	20% (n=2)	20% (n=2)	50% (n=5)
Communication in the team is open and honest.	10% (n=1)	0% (n=0)	20% (n=2)	20% (n=2)	50% (n=5)
Group meetings are very productive.	10% (n=1)	0% (n=0)	20% (n=2)	10% (n=1)	60% (n=6)
Members of the team trust each other.	0% (n=0)	0% (n=0)	20% (n=2)	20% (n=2)	60% (n=6)
Team members help one another deal with problems or resolve issues	0% (n=0)	0% (n=0)	33.33% (n=3)	11.11% (n=1)	55.56% (n=5)
Team members display high levels of cooperation and support.	10% (n=1)	0% (n=0)	20% (n=2)	10% (n=1)	60% (n=6)

Table 3: Student Reports about how well their Team Worked Together

How effectively team worked together	**Number of students**	**Percentage**
Poorly	1	10.00%
Adequately	2	20.00%
Well	2	20.00%
Extremely well	5	50.00%

Summary

The main objective of this work is to introduce students to hands on activities and learn the principles of research in specific areas of AM and medical devices. Students were able to experience the challenge of estimating the cost of AM and how to reduce the fabrication cost.

The project is not merely impacting the area of mechanics and design; it is also likely impacting other STEM-related disciplines. By providing students with hands-on experiences, concrete content knowledge and skills, and a multitude of opportunities to work alongside faculty and peers, it is likely that these experiences will be transferred over to other STEM-related disciplines. Students are learning valuable content and work/team skills. It is likely these skills will affect their work in other STEM areas. Additionally, as the approaches taken in this work are shared with other STEM educators, they may adopt or adapt some of the materials, resources and approaches for use with their students.

The data revealed that students found the workshop well organized, and informative, the activities were helpful and the presentations were clear (with all students strongly agreeing or agreeing). Students also agreed they had opportunities to work with other students and the workshop was what they expected. When asked to identify the most important things they learned, student responses aligned with the workshop content and goals. Interestingly, student response varied when asked to identify what they liked most about the workshop, although most responses described some aspect of the hands-on engagement. Finally, students reported the workshops did not need to be changed, as one student noted, "*everything was perfect and clear"*. In summary, based on the data reviewed to data, students were engaged and learning through participation in the workshops.

Acknowledgement:

NASA-MUREP Grant # NNX16AN19A and NSF grant # 1601522

References

Eyers, D., Dotchev, K., 2010. " Technology review for mass customization using rapid manufacturing". Assembly Automation, 30 (1), pp. 39 – 46.

Lipson, H., 2012. " Frontiers in additive manufacturing. The shape of things to come". The Bridge, 42 (1), pp. 5 – 12.

Kondor, S., Grant, C., Liacouras, P., …etc, 2013. " Personalized surgical instruments". ASME J. of Medical Devices, vol 7, no. 030934-2

Bain, K., 2004. "What the Best College Teachers Do". Harvard University Press; 1st edition, ISBN: 978-0674013254

Ma, R., Ding, H., Wei, J., Yang, D., 2013. " Verifying a software system for designing custom hip stems based on X-ray films". ASME J. of Medical Devices, vol. 7 No. 3, 031001-6