Additive Manufacturing: Instrumental Systems Used in Research, Education, and Service

Bahram Asiabanpour

1 Introduction

1.1 AM's Technological Advancements and Affordability

Additive Manufacturing (AM) applications, and consequently AM education has become a necessity for a variety of reasons, including AM's technological advancements and affordability, competition in the global manufacturing of products, and AM's positive role as an instrumental tool to use for different learning styles. AM, also known as 3D printing and freeform fabrication, is "A process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies." (ASTM 2900). Many AM processes, such as direct metal laser sintering (DMLS), fused deposition modeling (FDM), selective laser sintering (SLS), stereolithography apparatus (SLA), and 3D printing, have been developed in the past 30 years and are now commercially available. All commercial AM processes have at least one limitation in terms of materials choice, process speed, cost, part size, or accuracy as well as having final parts with low mechanical properties (e.g., porous body, brittle, low strength, etc.) (Hayasi and Asiabanpour 2013). In a panel that discussed the future of additive manufacturing at the 25th anniversary of the Solid Freeform Fabrication (SFF) Symposium in 2014 in Austin, TX, most of the participating experts agreed that future additive manufacturing systems should address functional metallic/multi-material and large-scale parts, utilize multiple processes, and allow built-in components in any part/system. Obviously low equipment and operating cost, speed, and energy efficiency are among the desired features of such systems. In addition to the technological advancements and better quality of the

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B. Asiabanpour (✉)
Ingram School of Engineering, Texas State University,
601 University Drive, San Marcos, TX 78666, USA
e-mail: ba13@txstate.edu

E. Pei et al. (eds.), *Additive Manufacturing—Developments in Training and Education*, https://doi.org/10.1007/978-3-319-76084-1_3

AM processes, the discussion panel forecasted that AM machines will generally be more affordable due to higher production volume and expiring patents (SFF 2014).

1.2 The Response to Global Competition

Engineering is vital to the future economic growth of the U.S. and the world. The globalization of the business environment, however, demands that engineers be equipped with new sets of skills. Some of the key characteristics that U.S. engineers should have are the ability to solve problems that account for "complex interrelationships" and "encompass human and environmental factors" (National Science Foundation publication 2007). Additionally, engineers are needed more than ever in the U.S. because (1) industrial processes are becoming increasingly complex and require more operators with high technical skills; (2) the need for research and development in materials and instruments demands engineers with advanced skills; (3) different socio-environmental factors such as an aging population, produce the need for more medical devices and equipment; (4) environmental issues and additional regulations need more specialists to maintain a safe and clean environment; (5) the growing need for energy demands more research and development to new alternative energy sources; and (6) the growth of the population and an aging infrastructure requires more development in variety of areas, including transportation, utilities, and communication further contributing to the need for more engineers in many different fields (The Perryman Group Report 2007). According to a report from the national innovation initiative summit, Innovate America, "innovation will be the single most important factor in determining America's success throughout the twenty-first century." (SME 1997) These two studies support previous findings of the Society of Manufacturing Engineers (SME) entitled "Manufacturing Engineering for the twenty-first Century" (Accreditation Board for Engineering and Technology 2002) and the criteria set by the Accreditation Board for Engineering and Technology (ABET). The SME study identified communication skills, teamwork, project management, business skills, and lifelong learning as some of the key competency gaps found in recent graduates of engineering programs. The ABET criteria (Wohlers 2014) maintain that "students must be prepared for engineering practice through the curriculum culminating in a major design experience based on the knowledge and skills acquired in earlier course work and incorporating engineering standards and realistic constraints that include most of the following considerations: economic, environmental, sustainability, manufacturability, ethical, health and safety, social, and political." The Wohlers report (2014) has forecast that the global market size for 3D printing industry will reach over $21 billion by year 2020 (Mohr and Khan 2015). Sebastian Mohr and Omera Khan summarized the variety of benefits and the impacts of the AM on global production and the supply chain (Salsman et al. 2013) (Table 1).

Table 1 The impacts of 3D printing on supply chains and supply chain management (Salsman et al. 2013)

Impact	Category
Mass customization	Customer co-creation Maker movement; Prosumers; Democratization of design; Markets-of-one Postponement
Changing view on resources	Circular economy; Higher material/resource efficiency; Sustainability attitude
Decentralization of manufacturing	Reducing assembly steps; Reducing parts and SKUs; Reducing the supplier base; New design possibilities
Rationalization of stock and logistics	Print-on-demand; Shipping designs, not products; Digital inventory; Change of inventory mix
Changing value-adding activities	New sources of profit; New cost base; Changing capital requirements; Collaborative manufacturing; 3D printing services
Disruptive competition	Reduced barriers to entry; Niche markets; Producer = investor = founder; Printing away from control

1.3 Undergraduate Student Recruitment and Retention in the STEM Field

AM education has become ever more important, as many industries are now utilizing it as a mainstream technology in their efforts and expect their employees to be skillful or at least familiar with the relevant AM technologies. Additionally, there have been many research efforts that indicate that many students from kindergarten to the undergraduate level (K-16) are either reluctant or uncomfortable with STEM topics and may drop them from their education if these students are not appropriately and guided. According to the National Science Board, one of the key challenges in engineering education is to overcome the inaccurate perceptions of engineering found among high school students and their parents and even their teachers. Surveys show that the general public is not fully aware of the engineering role in “improving health, the quality of life, and the environment.” (National Science Foundation publication 2007) This inaccurate public belief has resulted in the current stereotype that suggests only those students who are good at math and science and like working with objects rather than people enter engineering programs and those who like teamwork and finding solutions for social problems are alienated from entering engineering programs. “As a result, many students, especially women and minorities, cannot see themselves as engineers.” (National Science Foundation publication 2007) Additionally, the statistics show that women and minority groups do have higher dropout rates in engineering. The main causes of their abandoning engineering programs have been poor performance in “their first math courses,” “lack of role models,” and “perceptions of a too competitive and uncaring environment”. According to this report “retention of engineering students is a systemic problem that begins long before college.” (National Science Foundation publication 2007) Both perception and preparation play an influential role in these recruitment challenges and later the attrition rates in many engineering programs. Undergraduate research has been shown to be an effective learning practice and retention tool through delivering such benefits as knowledge base development, professional development, and strengthening of collegial efforts. Research by Salsman, N., et al. (Langley-Tumbaugh et al. 2014) shows that a student’s total hours working on research projects and the total time spent on the undergraduate research projects by a research mentor/faculty does significantly and positively correlate with perceived benefits that are recognized by students. They suggested that there be “heavy duty” involvement of students in the research process (Todd et al. 2015). The benefits of undergraduate research involvement for students with a disability (Prunuske et al. 2013; Stapleton et al. 2010) and underrepresented groups in STEM have been also reported (Carter 2011; Davis and Clark 2014). Early Undergraduate Research has been implemented and reported on by different institutions as well. Alma College, under a five-year NSF-STEP grant, offered a summer research program to first-year students to allow them to work in science research labs across the STEM disciplines. Upper-class students served as peer mentors in each of these research labs. This program produced an increase in the number of science majors; further, students participating in the program were retained at a higher rate than their peers; and participants had improved academic performance (Gibson et al. 2010). AM, as a relatively safe and low-cost technology, has been identified as a learning, recruiting, and retaining tool for those students enrolled in different Science, Technology, Engineering, and Mathematics (STEM) and non-STEM fields as well as K-16 levels. This chapter discusses and reports on a set of activities related to education, research, and service, including specific examples from Texas State University, in response to the key challenges raised by SME, ABET, NSF, and the Innovative America summits and are being implemented at the university level.

2 Additive Manufacturing Education at the Undergraduate Level

2.1 Additive Manufacturing as a Stand-Alone Course

In response to research and industry demand, the manufacturing engineering curriculum at Texas State University introduced an elective course for senior year undergraduate students. The course is open to engineering graduate students and includes additional tasks and assignments.

Table 2 Specific Outcomes of Instruction for the AM course

• Students will discuss the applications of Additive Manufacturing for a variety of fields including engineering, medical, and biomedical engineering
• Students will demonstrate and discuss a variety of Additive Manufacturing technologies
• Students will explain different aspects of software and tool paths for different Additive Manufacturing technologies
• Students will use multiple Additive Manufacturing software programs
• Student will apply selected Additive Manufacturing machines to produce parts
• Students will select the appropriate Additive Manufacturing process by considering technical requirements of the work and the financial aspects of the chosen process

Table 3 AM course cover topics

• Introduction and basic principles of additive manufacturing, freeform fabrication, and rapid prototyping
• Development of additive manufacturing technology
• The generalized additive manufacturing process chain
• Photopolymerization processes
• Powder bed fusion processes
• Extrusion-based systems
• Printing processes
• Sheet lamination processes
• Beam deposition processes
• Design for successful additive manufacturing
• Mass customization and personalization
• Rapid product development

2.1.1 Outcomes and Topics

Because the education of AM topics is new and the AM field itself may cover many different aspects, no established curriculum was readily available. Therefore, at first, just a set of expected outcomes was defined (see Table 2). Then, utilizing the available literature, a detailed list of topics was developed (Table 3). The textbook chosen for this course was Additive Manufacturing Technologies Gibson, I., Rosen, D., Stucker, B. (2015), as it reflects recent developments and trends of the AM in considerable detail (SME 2017). Additionally, SME's Additive Manufacturing Certificate Program Body Of Knowledge (Anderson et al. 2001), Wohler's report (Mohr and Khan 2015), and the personal research and development of several instructors in the field were included as lecture topics (Tables 2 and 3).

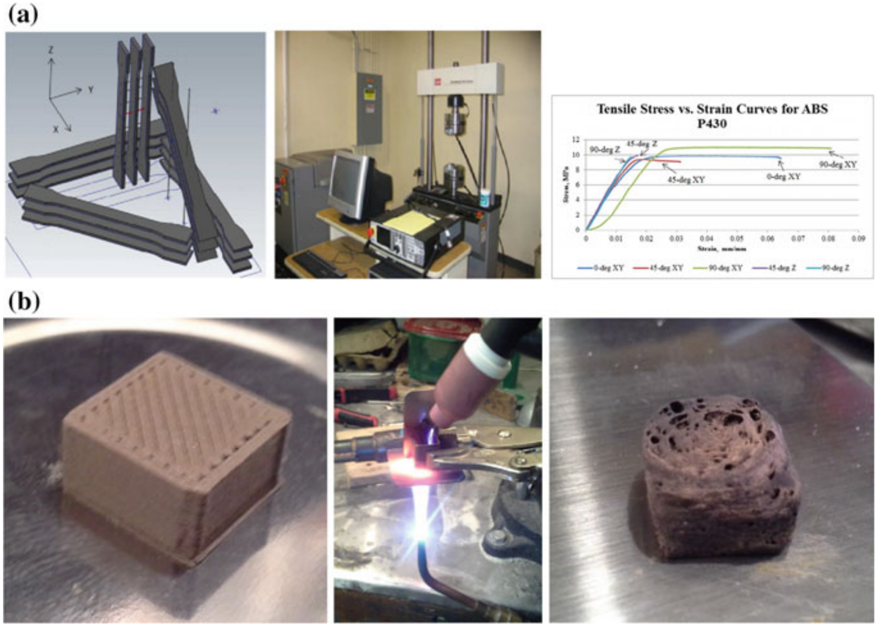

Fig. 1 Examples of the AM course projects: **a** an typical designs of experiments and tests and **b** an exploratory test on new ideas

2.1.2 Class Activities and Assessments

The AM class is organized as a three-hour class with one hour of lab activities. Additionally, two field trips, including one small business start-up and one large advanced metal AM center visit are as part of the class. Assessment of the class included quizzes (10%) and homework (15%) related to the topic covered in the previous week, a midterm (20%), and a final exam (30%) as well as a project (20%) and class active participation (5%). Since the AM field is continuously changing and improving, projects were utilized to offer the latest tools, software, and processes to the class. As a result, these projects were very flexible and included a literature review of new techniques/technologies not covered in the lectures (e.g., flexible electronics), experimental/optimization projects using currently available processes, or testing of preliminary ideas for future research. Students were assigned to teams based on their technical interests and schedules (Fig. 1).

The lab activities, depending on machine availability and running status could include the Fused Deposition Machine (FDM)/Uprint, Laminated Object Manufacturing (LOM), the ZCorp 3D printer model Z450, InVision LD 3D modeler by 3DSystem, Solid Scape Wax printer, and Form2 SLA; software related to each process, safety training, and basic material experiments. Additionally, to make the class more usable for the full diverse group of students with different learning styles, the lectures and PowerPoint slides were organized in Bloom's Taxonomy (Van Roekel

2008) and Universal Design for Learning (UDL), a research-based framework that facilitates the design of instruction for diverse learners (3D printers and 3D printing of news 2017). In this method, four categories of learning styles were considered including 1. Sensorial (sight, sound, and physical sensations oriented toward facts and procedures) versus Intuitive (memories, ideas, and insights oriented toward theories and meanings); 2. Visual (pictures, diagrams, graphs, demonstrations) versus Verbal (material presented orally or in written, textual form); 3. Active (engaging in physical activity or discussions, trying things out) versus Reflective (thinking things through); and 4. Sequential (linear, following logical progression, learning in small incremental steps), versus Global (holistic, learning in large leaps).

2.2 Additive Manufacturing Education in the Context of Other Courses

AM is no longer being seen as an apparatus, which by pushing a button, becomes ready to use the final product. Instead, in its many applications, it is seen as one of many available manufacturing processes. The application of AM for the 3Fs (Form, Fit, and Function) has become part of the ordinary tools available for both industry use and education sectors. Some AM processes are capable of only demonstrating the shape and general purpose of a design (Form). Certain more accurate AM processes can fabricate components to the tolerances required for assembly purpose tests (Fit). More advanced AM machines with improved material properties can also fabricate the parts that actually are doing the work (Function). The applications of AM have become widespread. Since many fields may not have enough resources or relevancy to utilize AM, they may not need a full-fledged AM course. Instead, they may adopt a course module or simply chapter on relevant AM topics. There is a wide range of fields, courses, and grade levels, however, that can benefit from AM processes. 3D printers and 3D printing news websites have demonstrated different examples of AM use in these classrooms (Asiabanpour and Sriraman 2006):

Biology	Cross sections of hearts or other organs
Chemistry	Molecules to study
Auto	Replacement or modified car parts
Cooking	Designing intricate molds or for ices and gelatins
Engineering	Prototypes of their ideas
Architecture	3D models of designs
History	Historic artifacts
Graphic Design	Artworks

In line with the need for 3D printed parts in the context of 3Fs for different manufacturing tasks in engineering courses at Texas State University and not all students are able to take an AM elective course, several course modules or projects have been made available to students. These students can then participate in AM activities and acquire enough knowledge and hands-on experience to be able to work

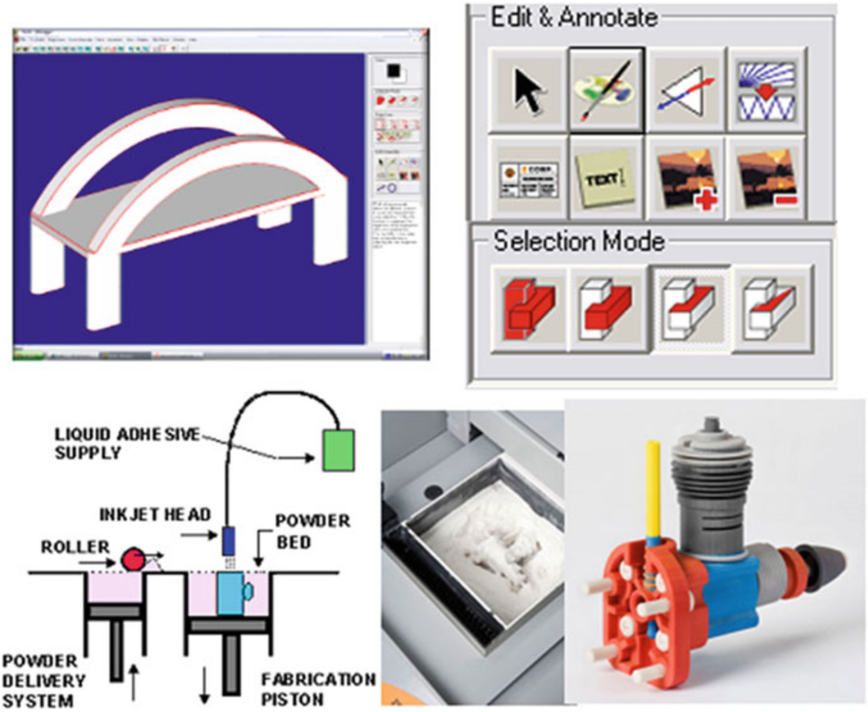

Fig. 2 Routine AM topics and activities utilized in the Tool Design class

with a variety of AM systems. Using this approach, AM is taught as part of the broader concept of product and process development. Students will have access to both Additive Manufacturing and newly developed Makerspace labs to complete their assignments and projects. Two major classes that offer AM course modules and training are Tool Design and Concurrent Process Engineering (a capstone class). In Tool Design class (Asiabanpour and Sriraman 2005), routine topics, including an overview of AM processes, certain AM software (e.g., ZEdit and ZPrint), and a few hands-on AM processes for special tooling (e.g., a model for a rubber mold) are covered (Fig. 2).

2.3 *Additive Manufacturing in Capstone Design Course*

The capstone senior design class is a semester-long (16 weeks) in which a team of 3–4 students complete their project on a real-world industry or research problem. In the class, students start their project with a need and a description for a specific application. They, then, follow a procedure to finalize their work. Major steps include team building and project management, identifying customer needs, innovation and

Fig. 3 Examples of AM applications in senior design projects: **a** NASA Mars core sampling system project; **b** Centrifugal force mechanism; **c** Light holder designing and fabrication, **d** Luminaire designing and fabrication, **e** Battery terminal cap prototyping followed by metallic mold design and fabrication, and **f** Keychain design, fabrication, and casting

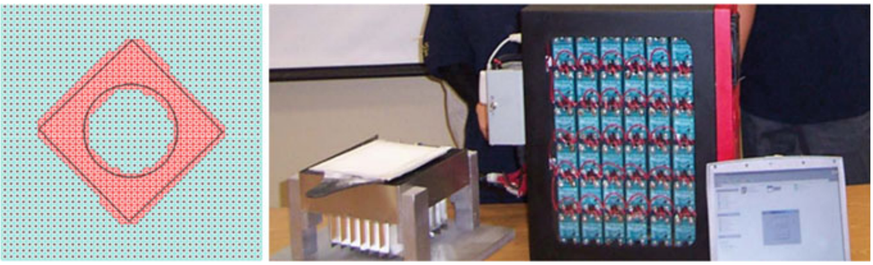

Fig. 4 Additive manufacturing process development as part of a senior design project: Heat element status for the Selective Inhibition of the Sintering AM process

creativity, defining product specifications and quality function deployment (QFD), concept generation, concept selection, design, design for X (manufacturing, assembly, safety, etc.), robust design and design of needed experiments (DOE), additive manufacturing and rapid tooling, manufacturing, assembly, testing, failure mode and its effects analysis (FMEA), and a business plan (Asiabanpour 2015; Asiabanpour et al. 2008). AM is taught in this capstone class as part of the product and development process. The students become familiar with the AM concept and AM equipment using a hands-on approach. Then, they apply their knowledge of AM and other processes to their own capstone projects. Figure 3 illustrates some of the products that have utilized these AM processes for completing a project.

Additionally, in senior design projects, some students conduct their research on new developments for additive manufacturing processes as well. These projects usually include design, manufacturing, and experiments on (Asiabanpour et al. 2007a, b; Asiabanpour et al. 2004, 2014; Asiabanpour and Hayasi 2013) (Fig. 4).

3 Research Activities on Additive Manufacturing

3.1 Research on Developing an Additive Manufacturing Process

The research activities leading to the development or improving the performance of a system require a variety of interrelated investigation and development processes. As an example, in this section, activities toward the development of the SIS are discussed in three segments (Asiabanpour et al. 2003a, b; Asiabanpour et al. 2004, 2006, 2009; Asiabanpour and Khoshnevis 2004; Khoshnevis et al. 2002, 2003): Analytical research, experimental research and developmental research (Fig. 5). These categories of activities are not independent of each other. Simultaneous theoretical study, experimental research, and software development and modification are conducted. After an analysis of each experiment, a new set of experiments, new machine

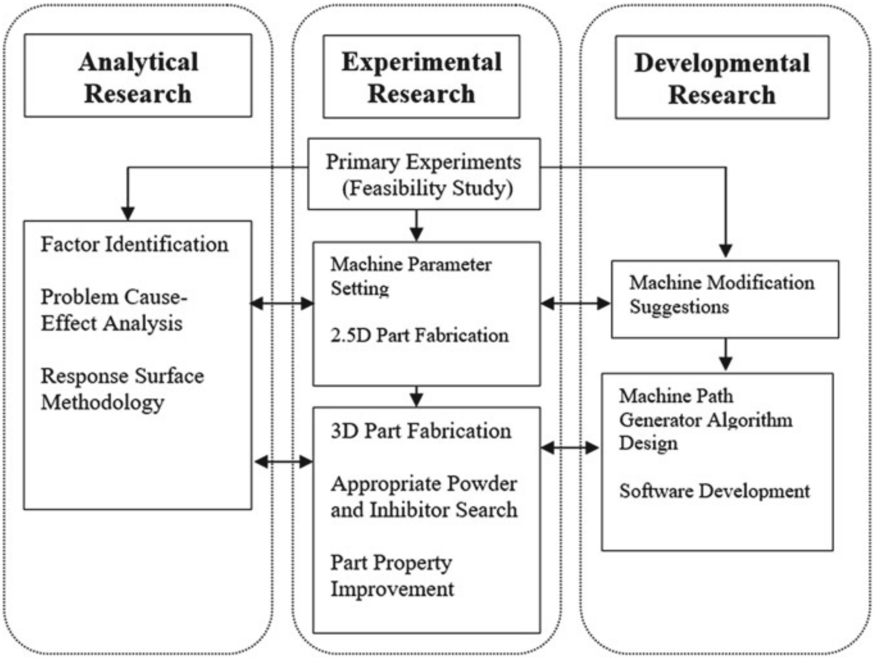

Fig. 5 General research and development activities for AM processes

and software modifications, or a new theoretical subject study are proposed and pursued. During developmental research, the machine path and hatch path generation of algorithms are designed and implemented based on the SIS process requirement for the fabricated alpha machine. In the experimental research, many 2.5D and 3D parts are successfully fabricated. Numerous experiments are also conducted to find the appropriate polymer and inhibitor for the SIS process. To determine the analytical research direction, a goal hierarchy plot was applied. There are different goal levels in that goal hierarchy plot.

3.1.1 Developmental Research

Hardware: An Alpha machine was designed and constructed to study the SIS concept. This machine included hardware, electronics, control, and user interface components (Fig. 6).

Software: Every rapid prototyping system has its own specifications. The part boundary form, the part filling method, and part separation from the surrounding material determine the machine (NC) path pattern for every layer. For the SIS process, the machine path and hatch path generation algorithms have been designed and implemented based on the SIS process requirement for the fabricated Alpha machine.

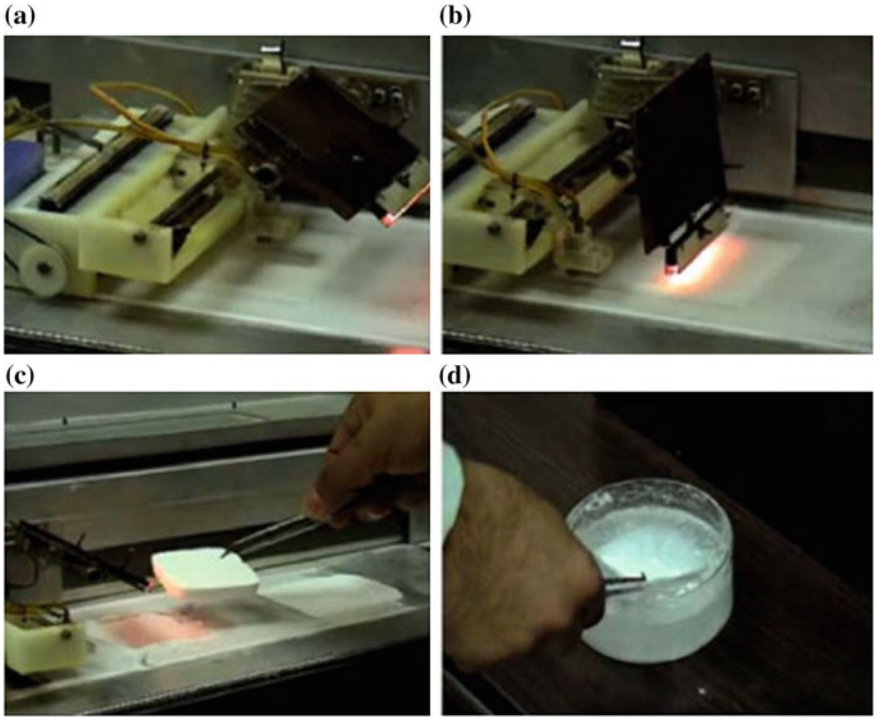

Fig. 6 SIS Alpha machine

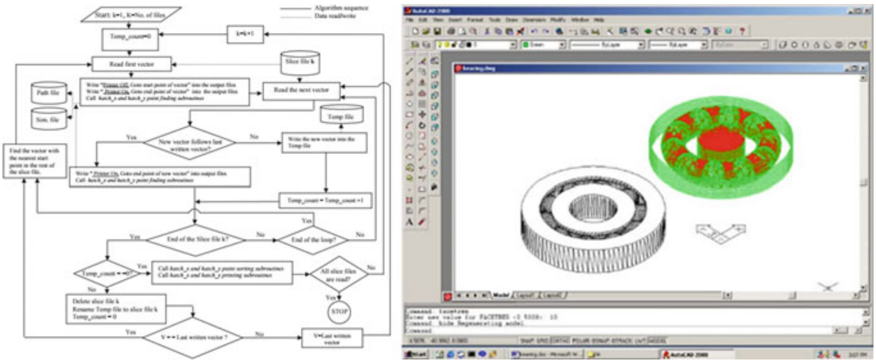

Fig. 7 Dedicated software development for the SIS AM process

The designed algorithm enables the system to generate an appropriate machine path file using a solid model file in the STL format with no limitation as to model size or complexity (see Fig. 7).

Fig. 8 Experiments and the fabrications of their parts

3.1.2 Experimental Research

In all experimental research, many material experiments and part fabrications are undertaken. For the SIS process, these include experiments with machine parameter variation (e.g., heater temperature, layer thickness, and printer feed rate), post-processing material variation (e.g., adhesive and wax), and variation of process steps (e.g., bulk sintering). Primary settings for factors in the conducted experiments at this stage were assigned using the one-factor-at-a-time method (Fig. 8).

3.1.3 Analytical Research

To design the analytical research direction, after developing the goal hierarchy, response surface methodology (RSM) was used to understand the several factors' affecting the objectives (accuracy, strength, and surface quality). In the SIS pro-

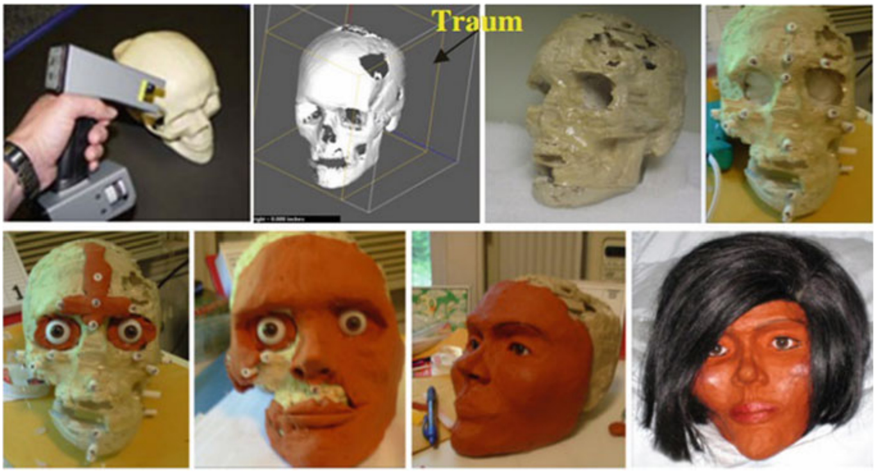

Fig. 9 Different stages of reverse engineering, CAD file improvement, AM, and face reconstruction needed to identify the person

cess, since multiple objectives were important, the desirability function method was applied to optimize the process (Palmer et al. 2006; Asiabanpour et al. 2008).

3.2 *Utilizing Additive Manufacturing for Applied Research*

Over the years, in many collaborative efforts with experts from other fields, AM processes have been utilized to serve research in different academic, industrial, and service sectors. The application generally fits under the 3Fs concept (Form, Fit, and Function). Figure 9 illustrates one of these collaborative works with a forensic anthropologist in the research to identify an unidentified skull (Asiabanpour and Wilson 2011; PCAST (President's Council of Advisors on Science and Technology) 2012).

4 Service and Outreach

In the last ten years, fewer students are choosing to pursue STEM careers. This is particularly true for U.S. students coming from underrepresented minority groups (http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-engage-to-excel-final_2-25-12.pdf). Too many students and parents now believe that STEM subjects are too difficult, boring, or exclusionary (PCAST 2010). In addition, although college-age Hispanics and African-American students are increasing as a percentage of the U.S. population, their participation rates in STEM fields remain significantly low (Sanders 2004). To address the ongoing issue of recruitment and retention of students (especially female and minority students) dif-

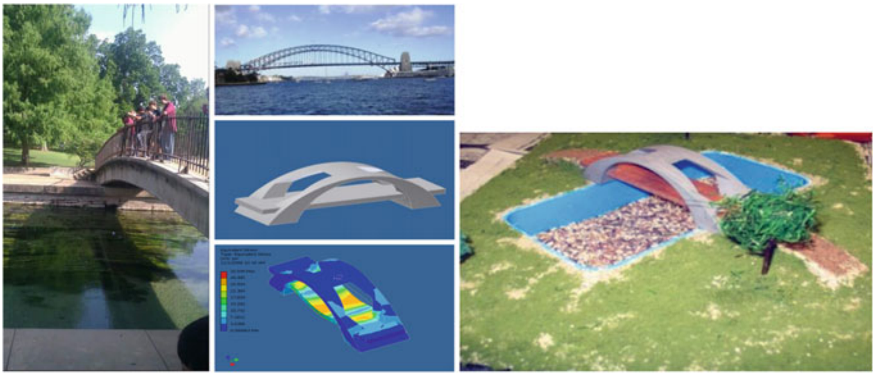

Fig. 10 Applying AM and other engineering tools in week-long engineering camps for K-12 students

ferent novel outreach approaches have been designed and implemented for middle school and high school students to familiarize them with engineering functions and engineering methods. Through this approach, students participate in a seven-day research camp and learn different engineering skills and tools, such as CAD solid modeling, finite element analysis, additive manufacturing, mechanical tests, team working, and communication skills using the project-based concept (e.g., a bridge design research project). Survey results at the end of the program showed a good understanding of engineering skills and its functions as well as high degree of satisfaction among the participants (Sanders 2004; Asiabanpour et al. 2010; Gourgey et al. 2010; Asiabanpour 2010) (Fig. 10).

5 Conclusion

The chapter presented the process of educating AM as a stand-alone course and as a process included in an engineering course. Additionally, it provided a variety of examples where AM has been utilized in research and as a service tool. The trend shows that applications of AM will grow, and it will become an ordinary tool of daily life. It is obvious that parallel to these research advancements educational expansions and daily use of AM that the safety and ethical aspects of these processes should also be taken seriously.

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Dr. Bahram Asiabanpour is an Associate Professor of Manufacturing Engineering and a Certified Manufacturing Engineer (CMfgE). He has served at Texas State since 2003 and is the director of the Rapid Product and Process Development (RPD) lab. Dr. Asiabanpour is PI or CoPI of 30 external grants. He is the author of more than 80 journal and conference papers and has coauthored with more than 50 students. He has taught 20 different undergraduate and graduate courses at Texas State. He is the editor in chief of the International Journal of Rapid Manufacturing (IJRapidM).

External Resources: Rapid Product and Process Development (RPD) Center at Texas State University–San Marcos is engaged in research and educational activities in design, development, automation and analysis of functional products, processes, tools and systems in diverse sizes, from micro scale to several yards, in a short period of time. The research effort is focused on functionality and customization based on the customer's needs. Development of mechanical and electromechanical systems for industry are of special interest at this center. http://rpd.engineering.txstate.edu.