THE PENNSYLVANIA STATE UNIVERSITY
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DEPARTMENTS OF INDUSTRIAL AND MANUFACTURING ENGINEERING AND MECHANICAL AND NUCLEAR ENGINEERING

THE DEVELOPMENT OF DIGI-NET AT THE PENNSYLVANIA STATE UNIVERSITY TO SUPPORT INTERDISCIPLINARY INNOVATION

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ABSTRACT

Digital fabrication tools, devices that can be used to transform a conceptual model into a physical one or vice versa, are frequently used for design purposes. Additive, subtractive, and input-driven processes constitute the gamut of possibilities within digital fabrication, and are explained in detail in this thesis. As a large research institution, Penn State has invested in many different types of digital fabrication resources, which are spread among a number of different academic colleges and departments.

The Digital Inquiry and Group Innovation Network, better known as DIGI-Net, seeks to enhance design processes for the Penn State community. This thesis describes the development of a website with a browsable database comprising all of the available digital fabrication equipment on campus, video and text training tutorials, conveniently-located kiosks, and easily identified graphic icons as the main components of DIGI-Net. The objectives of DIGI-Net are to enrich the resources available to the Penn State community at the confluence of design, technology, and academic inquiry. Specifically, DIGI-Net seeks to find and describe Penn State's digital manufacturing resources, collate these in a searchable database catalogued by machine characteristics, and create process descriptions, matching icons, training videos, text worksheets describing proper machine operation, interactive kiosks, and a print brochure that documents digital fabrication locations and interdisciplinary projects that have used these fabrication resources.

The goal of DIGI-Net is to democratize digital fabrication and make it easier for people to access, learn about, and use Penn State's resources. Prototypes of these services were presented at the spring Design Showcase. The objectives in the research are to identify a number of possible improvements in communication and temporal strategies in order to

maintain funding to ensure that DIGI-Net can exist in perpetuity. Future work to maintain innovation in DIGI-Net and measure its success within the community are also discussed.

So far, DIGI-Net has contributed significantly to its objectives. All digital manufacturing tools, located in ten different buildings have been identified and collated in the database. An effective classification scheme dividing resources into additive, subtractive, or input-based has been implemented. Process descriptions have been created to accompany all of the digital fabrication tools, and process icons have been developed for 19 different processes. Video and text tutorials have been created for the powder based printers, laser cutters, CNC router, and water jet cutter. A website searchable by process, machine type, and facility has been created. A kiosk with a touch screen that runs all of DIGI-Net's digital content has been fabricated. Finally, a print brochure summarizing six different interdisciplinary projects utilizing digital fabrication tools and Penn State's resources was printed for distribution.

Based on the findings, DIGI-Net has succeeded in creating prototypes of its future services, and there are a number of different improvements to make to the communication lines in place within DIGI-Net's organizational structure that may improve future work.

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CHAPTER 1

DIGITAL FABRICATION AND ITS PLACE AT PENN STATE

1.1 AN INTRODUCTION TO DIGITAL MANUFACTURING

Digital fabrication resources, as they are referred to in this thesis, are machines or processes capable of producing a physical or virtual 3-D model through additive, subtractive, or input-driven techniques. Additive processes begin with a liquid or powder parent material and transform some portion of it into a physical form by applying heat, light, or chemical agents. Subtractive processes cut, drill, burn, or melt material away from a work piece to arrive at the final form. The purpose of input-driven devices is to either accurately measure and collect data regarding a physical form to transform it into a digital 3-D model, or to create digital models via haptic feedback implements [1].

Machines taking advantage of these digital manufacturing processes are becoming increasingly popular as tools to reduce the time to market for production assemblies [1], as they represent systems through which designers can rapidly produce prototypes or assembly components at relatively low expense in comparison with traditional means such as plastic injection molding, casting, or forging. Parts produced from these machines oftentimes serve as valuable visual aids; industrial designers appreciate that models can provide tangible evidence of physical properties of a design, and marketing teams can use them to pitch products to investors or retailers [1]. Both emerging and fully-developed technologies under the digital manufacturing umbrella have received acceptance at many colleges and universities; Penn State is no exception.

1.2 CURRENT FABRICATION RESOURCES AT PENN STATE

As a research university, Penn State places great significance on the hands-on education of its charges. Both the College of Arts and Architecture and the College of Engineering have in place curricula that teach students design methodologies and prototyping techniques. Many of the courses reflecting this ideology utilize digital manufacturing resources to fabricate scaled conceptual prototypes, functional alpha prototypes, or components for custom assemblies. The College of Engineering, for instance, requires most undergraduates to participate in a senior capstone design course organized by the Learning Factory. Students in this course are placed into teams, often multidisciplinary by degree or background, and paired with corporate sponsors to complete a project under guidance from both an advising professor and the sponsor. In many instances, these projects culminate in a model, physical representation, or functional prototype of a conceptual design. Any number of machines in the stable of digital manufacturing resources at Penn State can be used to realize these models.

Utilization of fabrication tools is not limited to class work. Student groups such as Penn State Formula SAE take advantage of digital manufacturing resources for their ability to create precision-machined parts with great capacity for accurate repeatability. The culmination of Formula SAE's work, an open-wheel racecar, is seen in Figure 1. In addition to student groups of a design or manufacturing bent, those participating in independent study, graduate-level research, and extracurricular activities are frequent users of digital manufacturing equipment.

Figure 1: Penn State's Most Recent Formula SAE Competition Entrant [2]

Part of what makes studying the usage of digital manufacturing resources at a university so compelling is the necessarily educational atmosphere. A broad spectrum of user experience levels are encountered here at Penn State. Faculty are generally very well versed in using machinery required for their research. Staff members that operate centers of design and manufacturing at Penn State are the local experts on machine operating practices.

Of course, students are present in all phases of the learning curve. They can be found from the introductory to competency to mastery stages of digital manufacturing machinery. Some students learn to use machines as they are required for coursework and others become intimately familiar with the equipment through indulging their own curiosity and extra-curricular activities.

For financial, practical, epistemological, pedagogical, and experiential reasons, it is advantageous to reduce the barriers associated with students' becoming proficient in using digital manufacturing resources. Those with a broader and deeper comfort zone in a manufacturing setting are likely to bring parts to fruition more quickly, cheaply, effectively, safely, and with less hassle than naïve peers.

1.3 AN ARGUMENT FOR COLLATING DIGITAL RESOURCES AT PENN STATE

As the United States of America moves further toward a service-oriented economy, it is becoming increasingly important for universities to serve as ports-of-call for innovation. Students conferred with degrees must possess the aptitude and technical skills to continue innovation and lead these efforts outside of a classroom setting [3]. Penn State has committed to help its students innovate by providing them with cutting-edge fabrication resources that can be used to rapidly prototype, reverse engineer, create custom componentry, or visualize conceptual models. Open access to these tools will increase cross-talk between people of different disciplines, and this may assist in providing diverse solution sets to common manufacturing or fabrication problems. Although certainly a goal to strive towards, it is not essential that Penn State relocate all digital fabrication tools to a centralized location; rather, an ideological shift needs to occur. What has been proposed, namely, collating digital fabrication resources at Penn State, will have a number of positive impacts.

The most direct positive impact of increasing transparency between colleges and sharing resources will be reduced strain on equipment. For example, students in the College of Arts and Architecture frequently use a laser scanner in the Stuckeman Family Building to create layers for physical models to be used as visual tools for projects. As such, utilization of this machine increases at several points during the semester, making it a bottleneck in their coursework. Although students can sign up to use the machine for thirty minute intervals, doing so can be problematic if schedules conflict with open time slots or if rework is required after an initial run. If the College of Arts and Architecture had in place better communications with the College of Engineering, students could matriculate to the Learning Factory, for instance, to take advantage of their laser printer, a less-utilized resource.

Part of what complicates problems is the physical separation of resources. Since equipment is scattered throughout different campus buildings and belongs to different colleges and departments, there are different rules governing each machine. Hours of operation, safety certifications, permission to use equipment, methods of paying for machine time, and resources vary at each location.

Another advantage of creating a common bank of digital fabrication resources is increased collaboration. Studies consistently show that multidisciplinary teams display increased efficacy when compared with less diverse counterparts [4]. A 1996 article in the *Handbook of Work Group Psychology* noted that:

> For [creative decision-making] tasks, the available evidence supports the conclusion that team diversity is associated with better quality team decision-making. This effect has been found for diversity of many types, including personality, training background, leadership abilities, attitudes, and gender, and for top management teams diversity with respect to occupational background and education. [4]

Interactions between representatives of the College of Engineering, the College of Arts and Architecture, and the College of Information Sciences and Technology at the common interface of design and manufacturing certainly encompass many types of diversity. Circulation of students of different backgrounds within a working environment such as the Stuckeman Family Building studio or the Learning Factory has great potential to lead to collaboration between students, faculty, and staff who might not normally comingle.

Expanding access to manufacturing resources at Penn State will engender a "water cooler" effect whereby people with different interests, skill sets, experience levels, and disciplines serve as sounding boards for problems. For most of these problems, there is no right or wrong answer; a vast array of solutions is possible for most design prompts. The elegance of engaging in meaningful discourse with others is that it can spark new ideas or avenues of thought without requiring a course registration or textbook. One study suggests that academic interdependence, "weakened boundaries, increased mobility of ideas and skills across those boundaries, and increased interfield coordination of research objectives, strategies, and results" [5].

The effects of collating fabrication resources will have spheres of influence beyond the realm of University Park. Many student projects are completed with the goals of a corporate partner in mind. The increased breadth of possible solutions may have direct impact on industry, as solutions devised for class projects are often implemented in the field. There is reciprocity from industrial sponsors, which can be expressed as the exchange of information from companies to students or faculty who might not normally receive exposure to those fields. These partnerships are already beneficial; widening the canals in place to ease information exchange by collating fabrication resources will reinforce these reciprocities, making them difficult to stop once started. Interactions between students, industries, and faculty of different needs and disciplines will inspire better, more effective solutions for use in industry; as innovation is brought into the marketplace, corporate sponsors will be driven to implore academia for cutting-edge solutions that build on top of previous iterations of the cutting edge.

In order to bring about increased collaboration, optimized solutions, multidisciplinary teamwork, and do it all faster with fewer barriers, the present-day digital fabrication culture at Penn State needs to change. Open access to the resources utilized to create prototypes, custom-made precision parts, and reverse engineered solutions is the stated goal of Penn State's Digital Inquiry and Group Innovation Network (DIGI-Net).

1.4 THE ROLE OF DIGI-NET AT PENN STATE

DIGI-Net is a group of students, faculty, and staff at Penn State from numerous departments and colleges devoted to expanding access to Penn State's myriad manufacturing tools. Current members of the DIGI-Net project represent Engineering, Architecture, Graphic Design, and Information Sciences and Technology (IST). DIGI-Net leadership has identified several key components to the project. Almost all of the steps taken by DIGI-Net so far have been the result of interdisciplinary work. Just as a human requires coordination and communication between different parts of the body to take a step, DIGI-Net has made strides by incorporating its philosophy of encouraging multidisciplinary teamwork into its own organizational structure.

The motivations behind DIGI-Net are quite diverse. As a research institution, Penn State wants to expose as many students as it can to technology-forward educational implements. The rapid prototyping tools representing the majority of digital fabrication tools are at worst, significant improvements on their manual counterparts. In most cases, however, rapid prototyping allows for parts to be manufactured in ways never possible prior to the advent of those specific technologies. Penn State benefits greatly from students using these devices because the image given by a widespread use of technology is often the driving force behind corporate sponsors providing financial assistance for resources such as those located in the Learning Factory.

Furthermore, DIGI-Net may improve more than just the number of students taking advantage of digital fabrication tools. The provision of information regarding tools owned outside of one's home college or department should lead to more students crossing the traditional academic boundaries created by the separate academic colleges. This, in turn, leads to collaborative efforts that can spawn better and more innovative results than what is possible with the input of only engineers, only architects, or only graphic designers. This too, is of course of great benefit to both Penn State and its students.

Ultimately DIGI-Net, on its most basic level, gives information regarding different manufacturing processes available at Penn State's various fabrication facilities. Enlightening people to what is possible via instructional tutorials, safety instruction, and thorough descriptions is a powerful educational tool.

1.5 THESIS OBJECTIVES AND ROADMAP

Penn State is not alone in its goal to increase collaborative efforts and communications between its various colleges. Notably, the University of Minnesota and MIT have taken significant strides to blur those boundaries. This thesis also explores how DIGI-Net has acted on its expressed goals; how these services have been implemented and differ from those already available at other universities is also discussed. Lastly, this thesis sheds light on methods DIGI-Net can implement to retain its cutting edge. The objectives of DIGI-Net are to accurately identify and find existing fabrication resources, compile these into a database based on a number of classifications, create process descriptions and accompanying icons, film training videos, create brief worksheets to describe proper usage of each fabrication machine, design a touch-screen interface kiosk to display digital content, and design a print brochure that documents digital fabrication locations and interdisciplinary projects that have used these fabrication resources. The objectives of this thesis are to explore what other institutions have done to combat the closed-door mentality of academic colleges and manufacturing, discuss what DIGI-Net has done so far at Penn State, and suggest what might be done in the future to ensure further innovation.

In the next chapter, inspirations and the ideologies molding engineering and architectural curricula that have led to the "silos" present in American collegiate settings are discussed. DIGI-Net's organizational structure and objectives follow in Chapter 3 to provide context to the problem. Next, an assessment of DIGI-Net's shortcomings, results, and roadblocks encountered is explored in Chapter 4. Finally, as DIGI-Net is a dynamic rather than static project, recommendations for improving current work are made in Chapter 5 and accompany a set of potential future tasks that may yield expanded outcomes.

CHAPTER 2

REVIEW OF RELEVENT WORK AND LITERATURE

Although in many ways DIGI-Net is innovative for including so many aspects of digital fabrication, other universities have undertaken collaborative efforts to explore the confluence of design, technology, and academic inquiry. The goal for DIGI-Net is to lower the boundaries between academic colleges and departments at Penn State by providing access to the necessary tools to increase ones' fabrication knowledge base. Be it through the provision of online tutorials and safety training, hours of operation, or case studies designed to give others inspiration, DIGI-Net seeks to reduce design deficiencies in our future engineers, architects, and industrial designers.

2.1 RELEVANT PREDECESSORS

The DIGI-Net project, which provides a unique portfolio of services never before offered on a college campus, has taken many of its cues from previous projects found at other institutions. In particular, the foundation for DIGI-Net has been inspired by the *Digifab* project at the University of Minnesota and MIT's Media Lab.

2.1.1 UNIVERSITY OF MINNESOTA - DIGIFAB

Digifab: A guide to Digital Fabrication Processes and Facilities at the University of Minnesota and Around the Twin Cities is a short pamphlet published by a group at the University of Minnesota's College of Design [6]. The *Digifab* pamphlet serves many of the same purposes as DIGI-Net's publications. *Digifab* opted to utilize, exclusively in print form, process icons, maps, and machine descriptions much in the same way DIGI-Net has done at Penn State.

Maps are the central item of *Digifab*. Two different maps provide information for potential users; one is a map of the UM campus with important digital fabrication sites highlighted; the second is a materials and services map that describes the capabilities of each machine and compatible materials for each [6]. For all that *Digifab* accomplished, there are notable shortcomings. The decision to not include a web presence means that updates and changes cannot be made on the fly. The University of Minnesota may opt to add equipment, and locations of machinery may change, but unless *Digifab* chooses to reprint modified editions, it becomes a relic of the past. Considering the high costs of printing, it is not surprising that *Digifab* has not been updated since 2007. There is something to be said about the dynamic nature of web design; webmasters are able to make modifications to webpages at minimal cost, and these changes, unaffected by a printer's lead time, are instant. Users can access updated information immediately, which is of huge benefit at a university setting where normal machine availability may deviate for a vast variety of reasons.

Likely driven by high printing costs, the *Digifab* pamphlet has been made available to the public and can be purchased for $12 [7]. Making this publication unavailable gratis removed the demographic most likely to be positively affected by such a pamphlet: students. Though the price tag is modest, it probably deterred a significant number of students from taking advantage of this resource. Another oversight of *Digifab* was the lack of provided operating instructions. Descriptions of machines in this pamphlet are brief, high-level, and not intended for a technical audience. Should someone need to use a machine with which they are unfamiliar, *Digifab* would be of little assistance.

2.1.2 MIT - MEDIA LAB

MIT, a veritable factory for future first-class engineers, prides itself on providing students with in-depth talents relevant to their field. In many respects, this is what separates MIT from many of the other top engineering programs. William J. Mitchell, a member of MIT's Media Lab, describes the propensity to develop finely-tuned engineers with unique skill sets as a result of "subdividing science and engineering into increasingly fine-grained research areas that could be pursued by means of rigorous, in-depth specialization" [8]. In the 1980's, MIT president Jerome Wiesener noted this as a potential deficiency of MIT graduates, and sought to ameliorate the situation through the construction of the MIT Media Lab. The Media Lab currently exists as a coterie of students, faculty, and researchers operating with a $25 million annual budget. This annual budget is provided almost exclusively by 60 or so corporate sponsors. The Media Lab applies research "for envisioning the impact of emerging technologies on everyday life – technologies that promise to fundamentally transform our most basic notions of human capabilities" [9].

Both a unique physical location and organizational structure have served the Media Lab well. A new building, constructed within the last five years, is seen in Figure 2. The cafeteria, located on the top floor, forces patrons and employees alike to walk past most of the research facilities, which are visible to the atrium via expansive windows. Studio space in the Media Lab's building is reconfigurable, leading to increased on-the-fly interactions.

Figure 2: MIT Media Lab's Wiesener Building, as seen in 2010 [10]

Comb through a team at the Media Lab, and one would probably encounter people with backgrounds as diverse as engineering, art, industrial design, and music. Serving as a haven for multidisciplinary research, the Media Lab has gained worldwide recognition for producing many highly original, innovative results. The Media Lab is responsible for the digital inks that have made products such as the Amazon Kindle and Guitar Hero possible [9]. In fact, the Media Lab is so named because when it was established in the mid-80s, several rogue electrical engineers and computer scientists believed that "the human interface of computer systems was the coming thing" [8].

DIGI-Net does not aspire to construct a building at Penn State, but the Media Lab's triumphs and struggles provide a number of lessons that can be applied here. First and foremost, for the past twenty five years, MIT has proven that interdisciplinary study is highly beneficial, even if tangible benefits are difficult to quantify. Additionally, faculty devoted to this unique enterprise have piqued student interest in design; so, the goal of generating unique and creative designs by incorporating different disciplines has been amplified by the inclusion of people whose curiosity drove them to seek involvement in the Media Lab. Since the Media Lab exists on private funding, they are far from recession-proof. Research is occasionally scaled back at the behest of sponsors, and the financial liquidity of a company often determines its involvement in Media Lab projects.

The problem of private funding echoes beyond just research. Unfortunately, the Media Lab opted to independently fund construction of a new building at the turn of the millennium, with plans being approved in 2006. Just before breaking ground, two major donors rescinded their offers in light of our current economic recession; the Media Lab waited in the lurch for months before an anonymous donor filled part of the $50 million spending gap to complete a revised and much abridged version of the initial building [8].

2.1.3 DEMOCRATIZATION OF DIGITAL FABRICATION

The Fab@Home project born at Cornell University in 2006 has resulted in the development of several low cost 3-D printers capable of printing layered materials as diverse as icing, cheese, silicone, and cement. Fab@Home printer models can be purchased new for under $2,000 [11]. In comparison, Z-Corp 3-D printers similar to those owned by Penn State often cost upwards of $40,000 [12]. Another innovative tool bringing rapid prototyping to the masses is the RepRap. This device, also an additive 3-D printer, can be purchased for under $700. The RepRap is unique in many respects; it is run by open source code developed by a community of its users. More amazingly, the RepRap website contains downloads for RepRap owners that provide instructions for the RepRap to replicate itself. Over 50% of the components used in the first-generation RepRap can be self-replicated, meaning that a RepRap can be used to create both useful goods and more RepRaps [13].

DIGI-Net is opening doors of opportunity in ways similar to the RepRap and Fab@Home project. While these projects provide users with the physical resources to create 3-D objects, DIGI-Net supplies a breadth of easily absorbed information about Penn State's available digital resources geared towards both beginners and experts. The website, which will be replete with tutorials, training, safety certification modules, and contact information upon completion, is the keystone of DIGI-Net, as it contains all of the functional tools created for the project.

2.2 SIMILARITIES AND DIFFERENCES BETWEEN ARCHITECTURE AND ENGINEERING CURRICULA AT PENN STATE

2.2.1 ARCHITECTURE ACCREDITATION

The National Architecture Accrediting Board (NAAB) recognizes 123 institutions for providing professional degrees in architecture [14]. Although there are over 3,500 institutions providing undergraduate degrees in America [15], only 58 institutions are accredited to confer Bachelors of Architecture degrees. The limited appeal of architecture is based partly on the rigorous demands of the NAAB. Accredited institutions must provide at least 150 credit hours of instruction to grant students Bachelors of Architecture degrees (Penn State's program requires 162 credit hours) [14]; as a result, almost all programs last five years. Financial limitations and the ephemeral nature of student interests is often enough to drive away many potential candidates from architecture degrees.

Penn State's architecture students spend countless hours in studio, and like many others, the baccalaureate curriculum stresses the importance of learning in the studio environment. In fact, since 2004, NAAB accreditation has required programs to provide a written policy describing the studio culture [15]. Penn State's published policy states that:

> A healthy studio culture cannot be created by the faculty alone. It requires the full participation of our students. The academic setting is structured to encourage different viewpoints, various methods of teaching and inquiry, and the dissemination of knowledge by traditional and non-traditional methods … [At] Penn State, 'studio' is our short-hand term for a series of courses, but it is also a physical [location] which … places our students in a situation where they are able to learn at least as much from each other as they will learn from the faculty. [16]

Most architecture students encounter digital fabrication tools during their studio courses. Experiences with fabrication, as suggested by the architecture studio policy, should arise as much through traditional education as experiential methods. Documents crafted by national groups such as the American Institution of Architecture Students as well as Penn State faculty recognize the importance of an education based on extensive faculty/student dialogue. It is clear that the studio is intended to perfect technical skills, mold artistic philosophies, and act as a space where miscible ideas converge and spawn inspiration.

A 2008 survey recommended as a best practice that schools' "studio culture narratives should relate student educational experiences to the institution's broader learning culture and … recognize larger support networks and resources available to students throughout the larger institution" [17]. This suggested best practice echoes many of the sentiments of DIGI-Net's philosophy. While the Department of Architecture clearly values the importance of peer-to-peer learning within the studio environment as much as it does faculty-to-student instruction, broader initiatives to expand interdisciplinary learning have taken hold outside of Penn State. These interactions, indicated as a best practice for NAAB schools, would be one of the main benefits of DIGI-Net.

Architecture uses design to evoke emotions and reflect artistic motifs because architectural designs are highly visible. Aesthetic architecture does not always beget a feasible design. Famously, Frank Lloyd Wright proposed a design for a mile-high building to be constructed in Chicago and felt that its structural integrity was just as sound as any other building [18]. This building, *The Illinois*, is depicted in Figure 3.

Figure 3: The Illinois, by Frank Lloyd Wright [18]

Many components of architecture require calculation, and these tasks are normally contracted out to structural or architectural engineering firms, but the high-level design normally belongs to the architect, who considers him or herself more artist than scientist. To many architects, there is no such thing as an optimized design; personal taste dictates the "best" solution. DIGI-Net may provide the interface necessary to give architecture students solid grounding in the more technical aspects of their work.

2.2.2 ENGINEERING ACCREDITATION

The Accreditation Board for Engineering and Technology (ABET) criteria for accrediting engineering programs cites a number of required outcomes for all baccalaureate engineering programs. These include "an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice", "an ability to function on multidisciplinary teams", and "an ability to design a system, component, or process to meet desired needs within realistic constraints" [19]. Penn State's engineering curricula reflect the spirit of these outcomes. Required courses for graduating with a Mechanical Engineering degree include Mechanical Engineering Design Methodology (M E 340) and a capstone design course such as M E 440W [20], where students work in small teams to design different solutions to a common engineering problem.

Engineering does stress the importance of teamwork in problem-solving, but it does not put the same emphasis on peer-to-peer relationships as architecture. Due to the highly objective nature of most subject matter, peer input is not likely to yield incrementally better results than what could be achieved through consultation of textbooks. The notable exception to this rule is product design; although many engineering projects can achieve a single best design, the iterative nature of design still lends itself to critique and input from others. Because the Engineering mindset is structured towards getting the "right" answer, students are less likely to seek advice from others for design work and are more prone to disregard others' input.

Many instances of engineering design are not visible; so, it comes as little surprise that design appearance is often not of great significance to an engineer. Good engineering design is something that meets a number of technical requirements normally unrelated to aesthetics [1]. Achieving an optimal design is the lifeblood of engineers; form is a secondary concern to functionality and performance. On the other hand, a well-engineered product may not receive widespread acceptance if it cannot pass the muster of an image-minded consumer. Again, DIGI-Net's focus on human interaction seeks to provide students with access to the tools to sacrifice little in the way of appearance in achieving a well-engineered solution.

2.3 SUMMARY

The *Digifab* pamphlet created at the University of Minnesota has provided a roadmap for much of DIGI-Net's published material. The use of process icons, colorful and engaging maps, descriptions of processes, and case studies are all elements that DIGI-Net has recycled and refreshed. DIGI-Net hopes to have a more lasting impact than *Digifab* by taking advantage of several different media, making the entire resource free, and providing a unique set of services.

The Media Lab, arguably one of MIT's most important research arms, has for the past 25 years sought to expose the world to innovative solutions to mundane, but significant, problems. These innovative results have come under the guidance of multidisciplinary teams that have consistently shown the ability to achieve because, not in spite of, their differences. The success of people in diverse teams has become the backbone for arguing the continued existence of a project like DIGI-Net. The more Penn State is able to create innovative environments in which thinking is done in unique ways, the better this university will be represented on a global stage.

In many ways, the degree requirements listed by ABET and NAAB are very similar; both stress the importance of design, aptitude with common industry implements, and an ability to function as both an individual and team member. Engineering and Architecture, however, use different ends to justify these means. Although design abilities often define the skill of engineers and architects, it is a quality of paramount importance for both disciplines, albeit different reasons.

What DIGI-Net seeks to do is meet at the convergence of many disciplines at the design phase and catalyze deeper, more meaningful interactions between people of different disciplines by lowering the barriers to shared fabrication resources. The next chapter discusses the specifics of the DIGI-Net project; a description of the basic processes encompassed by the term "digital fabrication" follows. The results, outcomes, and issues faced by DIGI-Net are explored after this summation of our efforts to date. Finally, a set of recommendations are made for DIGI-Net's future work.

CHAPTER 3

DEVELOPING DIGI-NET AT PENN STATE

3.1 THE ORGANIZATIONAL STRUCTURE OF DIGI-NET

Regular meetings were held regularly beginning in the Fall 2009 semester with the goal of presenting a beta version of DIGI-Net's services at the semi-annual Design Showcase, held in April 2010. After assembling a crew of interested parties representing Architecture, Engineering, Graphic Design, and IST, teams were assembled to tackle different aspects of DIGI-Net. One team's responsibility was to enlist the support of expert staff members to help record video tutorials detailing each machine. Another team's goal was to successfully code a database of all the available digital fabrication resources using the MySQL query language. Common process icons, logos, fonts, and color schemes were developed by yet another team. A functional kiosk was constructed and designed by a set of architecture and engineering students in fulfillment of a senior capstone project. All of these directives were brainstormed at regularly held group meetings, which were administered by a set of faculty from the College of Engineering and the College of Arts and Architecture. A Venn Diagram in Figure 4 shows how each represented discipline interacts on DIGI-Net's different projects.

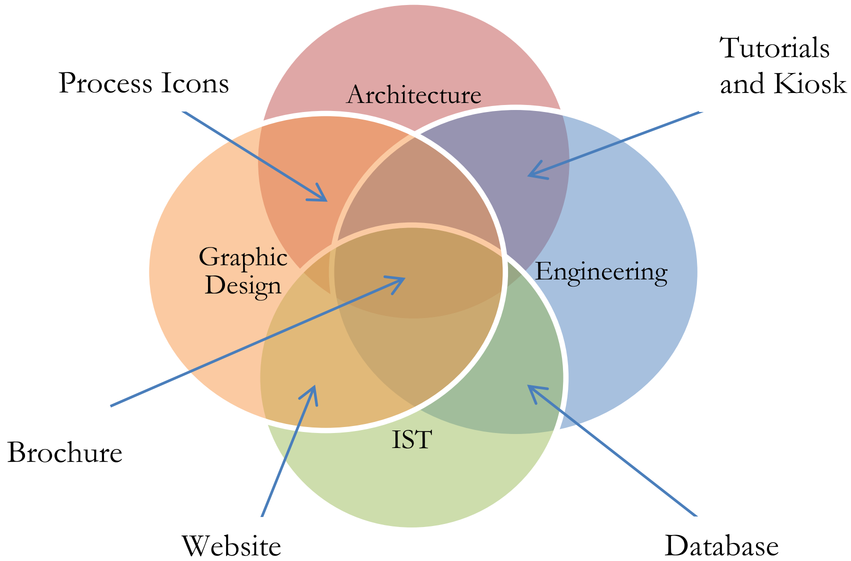

Figure 4: DIGI-Net Group Responsibilities and Interactions

DIGI-Net is in many respects a natural offshoot of the Learning Factory. Such facilities exist at a number of institutions in the United States and Latin America, but Penn State's version houses a number of rapid prototyping and digital fabrication tools in addition to traditional lathes, mills, and metrology, welding, and hand tools. The Learning Factory, formally created at Penn State in 1993 following a $2.75 million grant from the National Science Foundation [21], stresses an integration of:

> design, manufacturing and business realities into the engineering curriculum … In a typical day, a visitor might see a computer science student building a mobile robot, or EE and MEs arguing about the best way to machine an instrumented payload that will fly on a NASA rocket. A group of high school students of a troop of Girl Scouts might be dissecting toasters, while an entrepreneur waits for her latest concept model to be completed on the rapid prototyping machine. [3]

The interplay of different areas of educational expertise is something that DIGI-Net furthers. The Learning Factory is no doubt an excellent resource for engineering students, but there is no reason it cannot be equally useful for students from other Penn State colleges. Reciprocity of manufacturing resources at Penn State can lead to a resurgence of innovation though hands-on learning. In a publication lauding the Learning Factory, 88% of students surveyed say that "they learn better from hands-on experience than lecture" [3]. This hands-on approach also increases the confidence of students, as 80% of those polled have increased confidence in their abilities to self-instruct and 78% feel that they can solve real problems following the applied training [3].

DIGI-Net hopes to expand the hands-on learning experiences that can be drawn from fabrication to create more well-rounded students. While lectures and other traditional means of education form a backbone of conceptual information on a given topic, the applied methodology of the Learning Factory and the Stuckeman Family Building studio provide knowledge on a wide set of skills that can be used in a diverse set of real-life applications. The feedback from students on these facilities has been overwhelmingly positive, and those opinions have been reinforced by the responses of corporate sponsors. DIGI-Net encourages exploration of these resources; taking advantage of these tools broadens horizons, educates, forges relationships, and creates a palette of useful skills that can be drawn upon in graduate school or industry.

DIGI-Net's online presence means that it has a potentially global customer base. However, the main users of DIGI-Net's services are those granted immediate access to Penn State's manufacturing tools: students, faculty, and staff. There are no limitations on who in this group can benefit from learning about the manufacturing tools here. The ultimate benefits of DIGI-Net span much further than to just its main users, as industrial partners often reap the benefits of work accomplished with the assistance of these digital fabrication tools. Class projects and industry solutions are commonly the reason that people use the machines, but there are a number of different artistically or practically-driven extracurricular uses of these devices. In recent years, there has been a movement to democratize rapid prototyping [9]. Penn State has been an active proponent of this movement through construction and funding of facilities such as the Learning Factory, which is open to any student with the proper safety training and certification. Other projects have broadened the spectrum of digital fabrication users in a number of different ways. Over the years, the Learning Factory has expanded its presence on campus significantly. The increasingly interdisciplinary nature of this facility is demonstrated in Figure 5.

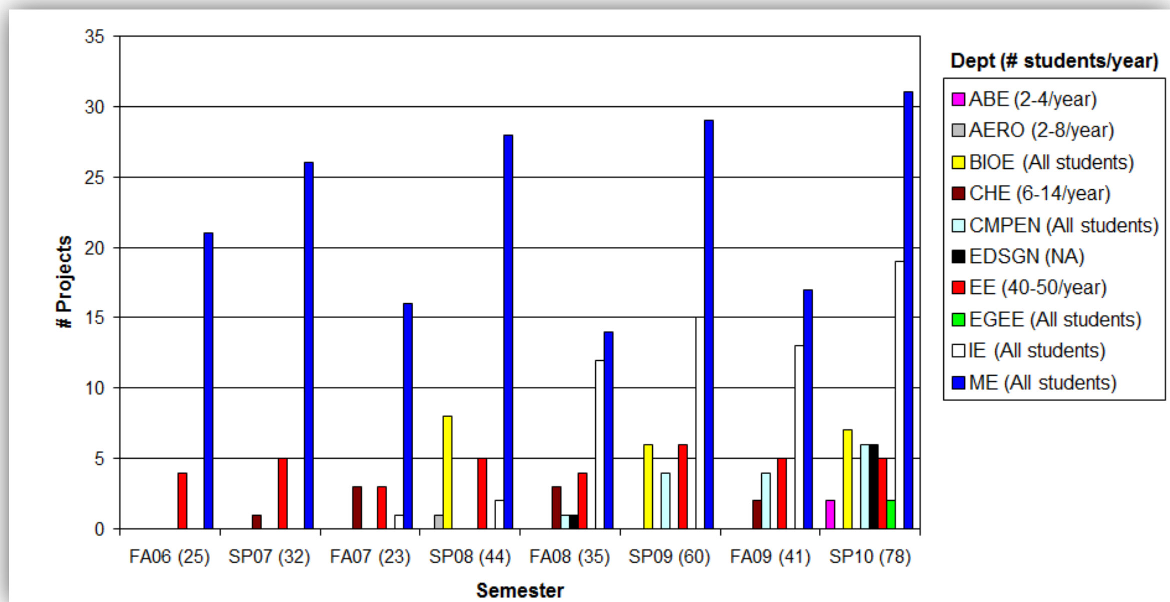

Figure 5: Usage of the Learning Factory per Semester by Department [22]

At present, DIGI-Net is comprised of students, faculty, and staff representing three of Penn State's thirteen colleges. Members from the College of Engineering, College of Arts and Architecture, and College of Information Sciences and Technology all play roles on a number of functional teams within DIGI-Net's structure. Active faculty members represent both the College of Arts and Architecture and the College of Engineering, and members of the College of IST have been helpful in rousing student interest within that college for this project.

The DIGI-Net project has a number of services in order to reach demographics of consumers that may benefit from tools provided in different media. The online component includes almost all of DIGI-Net's services; the website, when complete, will include maps, training, text and video tutorials, and an interactive database. Service kiosks placed around campus will either have direct access to the website or access to analogous content as the website. Finally, print media will be used both for student and promotional use. The brochures include a map of machine processes available across campus as well as case studies of what has been created using different digital fabrication methods.

3.2 WEBSITE, DATABASE, AND PROCESS ICONS

Perhaps the most far-reaching of DIGI-Net's proposed solutions is an interactive website capable of guiding users through several levels of questions that help identify potentially promising methods of fabrication. This iterative screening process is performed by gauging a user's required material characteristics, such as strength and appearance, budgetary constraints, time limitations, and requisite safety certifications. The website relays information for these inquiries from a linked database. In this database, rows are populated by information regarding individual machines. Information includes operating costs, hours of operation, necessary safety certifications, fabrication process type, expert points of contact, location, material limitations, and a list of case studies that exhibit achievable results.

The website, created using coding from IST and Engineering team members, uses a database populated by Engineering and formatted by IST members. A sample of the table used to populate the database is shown in Table 1. The full table can be found in Appendix A.

Table 1: Sample Data used in SQL Database [23]

sqlite_query($db , "CRE	, Material_Limits CHAR(	Building CHAR(255), Ma		sqlite_query($db , "CREATE TABLE MachineList(id INTEGER PRIMARY KEY
sqlite_query($db, "INSE	30in X 16in X 20in' , 'Defi	Leonhard Building' , 'CN		sqlite_query($db, "INSERT INTO MachineList VALUES (1,'VF2 Vertical CNC
sqlite_query($db, "INSE	31in X 16in X 20in' , 'Defi	Leonhard Building' , 'CN		sqlite_query($db, "INSERT INTO MachineList VALUES (2,'VF2 Vertical CNC
sqlite_query($db, "INSE	40in X 26in X 25in' , 'Defi	Leonhard Building' , 'CN		sqlite_query($db, "INSERT INTO MachineList VALUES (3,'VM3 Vertical CNC
sqlite_query($db, "INSE	30in X 16in X 20in' , 'Defi	Leonhard Building' , 'CN		sqlite_query($db, "INSERT INTO MachineList VALUES (4,'VF2 Vertical CNC
sqlite_query($db, "INSE	20in X 16in X 20in' , 'Defi	Leonhard Building' , 'CN		sqlite_query($db, "INSERT INTO MachineList VALUES (5,'VF0 Vertical CNC
sqlite_query($db, "INSE	20in X 16in X 20in' , 'Defi	Leonhard Building' , 'CN		sqlite_query($db, "INSERT INTO MachineList VALUES (6,'VF0 Vertical CNC
sqlite_query($db, "INSE	262mm X 508mm, 211m	Leonhard Building' , 'CN		sqlite_query($db, "INSERT INTO MachineList VALUES (7,'SL20T CNC Lathe' ,
sqlite_query($db, "INSE	432mm X 864mm, 254m	Leonhard Building' , 'CN		sqlite_query($db, "INSERT INTO MachineList VALUES (8,'SL30T CNC Lathe' ,
sqlite_query($db, "INSE	262mm X 508mm, 211m	Leonhard Building' , 'CN		sqlite_query($db, "INSERT INTO MachineList VALUES (9,'SL20 CNC Lathe' ,
sqlite_query($db, "INSE	262mm X 508mm, 211m	Leonhard Building' , 'CN		sqlite_query($db, "INSERT INTO MachineList VALUES (10,'SL20 CNC Lathe' ,
sqlite_query($db, "INSE	262mm X 508mm, 211m	Leonhard Building' , 'CN		sqlite_query($db, "INSERT INTO MachineList VALUES (11,'SL20T CNC Lathe'
sqlite_query($db, "INSE	10in X 10in X 12in' , 'Defi	Leonhard Building' , 'FD		sqlite_query($db, "INSERT INTO MachineList VALUES (12,'Dimension 1200 F
sqlite_query($db, "INSE	12in X 12in' , 'Defined by	Leonhard Building' , 'ED		sqlite_query($db, "INSERT INTO MachineList VALUES (13,'Wire EDM' , 'na' ,
sqlite_query($db, "INSE	8in X 8in' , 'Defined by m	Leonhard Building' , 'ED		sqlite_query($db, "INSERT INTO MachineList VALUES (14,'RAM EDM' , 'na' ,
sqlite_query($db, "INSE	10in X 10in X 10in' , '$8/c	The Learning Factory' , '		sqlite_query($db, "INSERT INTO MachineList VALUES (15,'FDM 2000' , 'Strat
sqlite_query($db, "INSE	20in X 10in X 10in' , 'N/A'	The Learning Factory' , '		sqlite_query($db, "INSERT INTO MachineList VALUES (16,'3D Printer' , 'Alleg
sqlite_query($db, "INSE	30in X 20in X 20in' , 'N/A'	The Learning Factory' , '		sqlite_query($db, "INSERT INTO MachineList VALUES (17,'EZTrak CNC Man

The website also has an interactive map of campus that shows each process and machine available at different locations. Different process types are represented on the map by graphical icons that have been developed by the Graphic Design team with input from Engineering and Architecture. From this map, users can select a machine to inspect. A separate page for each machine repeats characteristics given by the database and provides users with a set of tutorials to download. A screenshot of the map used on the website is shown in Figure 6.

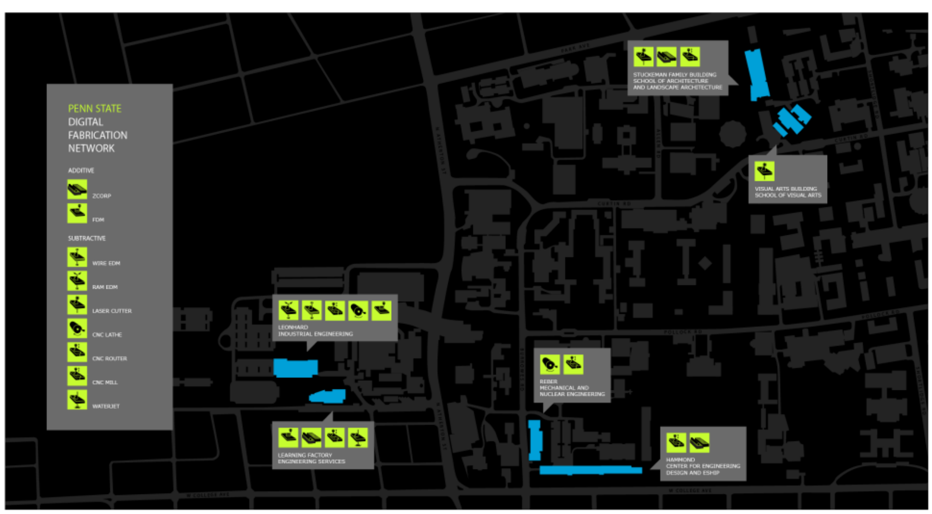

Figure 6: The final map used for DIGI-Net's website [24]

The tutorials, developed through collaborative efforts involving Engineering and Architecture teams, are geared such that users can benefit from them regardless of skill level or physical location. Two tiers of tutorials will be made available to provide information to either beginner or advanced users. Each tutorial will be available as a video file and as a document that can be printed out and brought along to a remote location as a step-by-step instruction manual. The video tutorials have capabilities similar to that of a DVD; menus and individual chapters allow users to skip ahead to sections relevant to their interests or needs.

As the DIGI-Net website serves as the framework upon which DIGI-Net's suite of services can be accessed, it was important that the website design team develop a set of pages that properly executed the vision of DIGI-Net administrators. The website incorporated graphic design elements used in the brochure and kiosk to accent an interactive database that leads patrons to machine tutorials, text training documents, and other information. PHP, a scripting language used with HTML, was used to code the website because of its flexibility, and MySQL was incorporated into the database language because it was relatively easy to learn to program and provided a robust database for the dynamic DIGI-Net webpage.

The graphic design team in particular sought considerable feedback during group meetings. During one particular meeting, a heated discussion arose on the issue of font size. Although the difference in font size may seem frivolous to an outsider, this scenario is demonstrative of the passion on display during every group meeting. Prospective process icon and logo samples for each machine were brought to each group meeting, and the comments generated by these discussions were generally reflected in future work. The final

DIGI-Net logo, seen in Figure 7, is the result of many changes and restarts. The tails of both the "D" and "N" are exposed to the white space outside of the blue circle. Appropriately, these open ended letters are evocative of subtractive machine processes that create a kerf from the edge of stock material to begin cutting its intended pattern in the interior portion of the work piece.

Figure 7: DIGI-Net's Logo [24]

At its most basic level, DIGI-Net's goal is to supply students with access to a set of tools that can be used to take advantage of the myriad of manufacturing processes that have become integral in rapid prototyping, fabrication, and other phases of design. On the DIGI-Net website, a set of prompts leads the browser to a set of appropriate manufacturing tools specific to the scope of their envisioned product. Each manufacturing process has inherent strengths and weaknesses derived from their range of accepted materials or underlying technologies. One of DIGI-Net's strengths is that it provides a bridge for someone with no experience in manufacturing to learn about various manufacturing methods and start to become competent users of this machinery. This thesis aims to shed light on the array of equipment represented by DIGI-Net. The additive, subtractive, and input-driven processes representing the gamut of digital fabrication tools encompassed in Penn State's digital fabrication network are described next to provide context for further discussion.

3.2.1 ADDITIVE PROCESSES

Additive processes begin with an indeterminate amount of material. Application of heat, electricity, chemical agents, or light is used to transform these materials into a discrete, solid form. In most cases, these formative processes are followed by some type of finishing process to reach the final dimensions and material properties. Penn State is home to a number of machines capable of performing additive fabrication processes.

Fused Deposition Modeling (FDM) machines create parts by extruding molten thermoplastics through a heated nozzle that can translate in two directions. A third degree of freedom is added by the bed upon which parts are constructed. This bed moves up and down in increments equal to the layer resolution size, which is generally between .007" and .013" [25]. As polymer exits the nozzle, it almost immediately solidifies and fuses to the previous layer. FDM machines possess the capability to model features that are not self-supporting through the use of a secondary nozzle that extrudes a brittle, water-soluble polymer. This material can be broken off of the model or washed away, but during the building process, serves as scaffolding upon which the modeling material fuses to form complicated elements. The process icon developed by DIGI-Net's Graphic Design team is featured in Figure 8, and a typical FDM machine is shown in Figure 9.

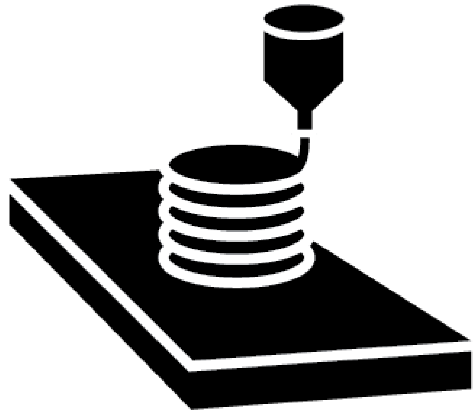

Figure 8: The FDM Process Icon [24]

Figure 9: FDM Machine [26]

Powder Bed Printing utilizes an inkjet printing head to spray a binding agent onto a layer of gypsum or other fine, low-moisture powder such as cornstarch. These apparatuses are commonly referred to as 3-D printers. The inkjet sprays a bonding agent in a pattern consistent with cross-sectional profiles of the desired shape. The layering process is achieved by a movable build area that recesses after each pass of the inkjet head. A roller spreads a fresh layer of powder on top of the newly bonded material, and the process iterates to completion. Since parts are encased by free powder, overhangs, independent elements, and non-supported structures are all feasible. Parts created through this process are initially fragile, but impregnating the porous form with superglue is a strategy frequently employed to improve material properties without significantly altering dimensional accuracy. A preliminary process icon developed for 3-D printers is seen in Figure 10, followed by a picture of a powder bed printing machine in Figure 11.

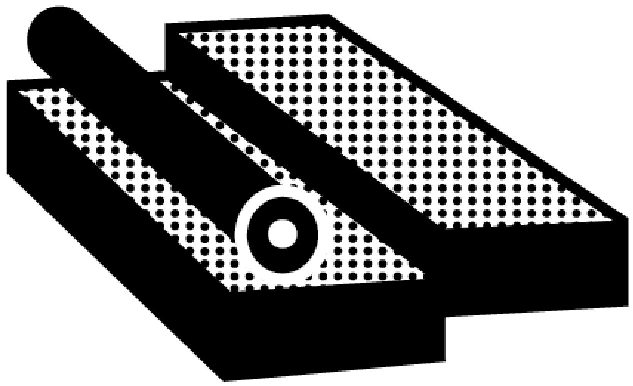

Figure 10: Early Powder Bed Printing Process Icon [24]

Figure 11: A ZCorp 3-D Printer [27]

Laser Engineered Net Shaping (LENS) is a 3-D printing process developed by Sandia National Laboratories. This method is capable of creating non-porous metallic parts by exposing metal powder to a high-power laser that melts the powder. A moving build tray with three degrees of freedom moves in the tool paths specified by the CAD model to create the final form. These parts can be altered in a number of different thermal or machining processes to achieve particular material properties and surface finishes [28]. Figure 12 shows the process icon developed for LENS.

Figure 12: LENS Process Icon [29]

Selective Laser Sintering (SLS) is used to create prototypes from powder metals or plastics. The build area is very similar to that of a 3-D printer. In this case, the inkjet head is replaced by a device that releases a high-energy laser beam that causes the metal powder to sinter. To reduce internal stresses in parts as they form, the build area is kept at an elevated temperature throughout the build process [30].

3.2.2 SUBTRACTIVE PROCESSES

Subtractive processes, as the name implies, take stock and carve, cut, burn, or melt away undesired features to arrive at a final form. As with additive processes, these machines utilize computer-aided design and computer-aided manufacturing software that supply the nominal geometries describing a particular part and the necessary tool paths required to obtain a desirable result. While some subtractive processes are simply automated versions of analog machines whose predecessors date to the Industrial Revolution, others are truly unique evolutions of modern technology that have been adapted to manufacturing.

Computer Numerically Controlled (CNC) processes represent a number of different machines in the category of subtractive digital fabrication processes. CNC processes translate a user-defined code (open source or G-code) to drive milling, turning, facing, routing, or drilling operations. Most CNC machines are capable of machining wood, plastic, metal, or stone when equipped with the appropriate head [31]. The digital daffodil, created by Penn State students and featured in Figure 13, is an example of what can be accomplished using a variety of CNC processes.

Figure 13: The Digital Daffodil [24]

CNC mills are best described by their degrees of freedom. The most complicated of these are capable of translation in all three axes as well as the three different modes of rotation, resulting in six degrees of freedom. CNC milling equipment universally possesses a chuck affixed to a rotating spindle and a moving work table. A work piece is mounted to the work table, and a cutting tool is inserted into the chuck. Once a program has been initialized, the rotating cutting tool removes material from the work piece in a pre-determined sequence of tool paths. CNC mills are useful for drilling, milling, or facing. Miniature versions of CNC mills are frequently used to mill away copper from printed circuit boards (PCBs). Mechanically removing copper from circuit boards serves as an alternative to chemical etching of PCBs; it has a reduced environmental impact and does not require a curing period [31]. The CNC mill process icon is shown in Figure 14. A typical CNC mill is seen in Figure 15.

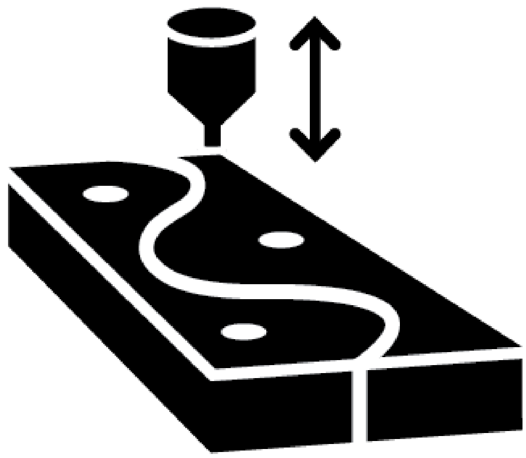

Figure 14: CNC Mill Process Icon [24]

Figure 15: Haas VM3 Vertical CNC Milling Machine [32]

CNC routers possess most of the same capabilities as CNC mills, but they are better suited for certain applications. Routers have much higher spindle speeds than mills and normally have a much larger working area, often as large as 4' x 8'. Routers are less deft with hard materials such as metal as a result of increased cutting tool deflection, which is a function of the higher spindle speed [31]. However, the spindle speeds found on many routers make them perfectly suited for projects requiring clean cuts, such as crown moldings or cabinetry.

CNC lathes remove material from a rotating work piece using any number of stationary turning or facing heads. The work piece, be it wood, plastic, or metal, is affixed to a chuck on a rotating head stock. G-code dictates to the software the rotational speed of the head stock as well as the movements of the carriage or tail stock holding the cutting tool [24]. The CNC lathe process icon is shown in Figure 16, and a Haas SL-20T, from Penn State's FAME Lab, is shown in Figure 17.

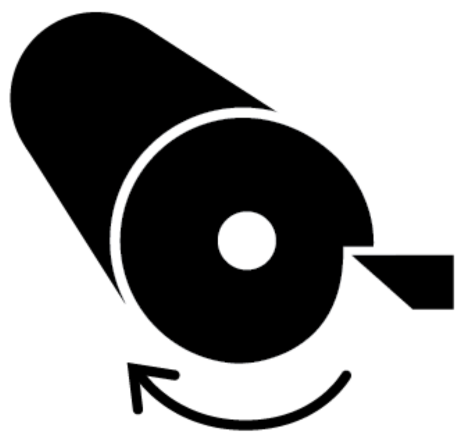

Figure 16: CNC Lathe Process Icon [24]

Figure 17: Haas SL-20T CNC Lathe [33]

Laser cutters are capable of cutting or etching chipboard, cardboard, Masonite, wood, leather, or acrylic with extreme precision. Laser cutters are capable of either cutting entirely through material or creating a raster image on the surface of the work piece. A laser restricted to two linear degrees of freedom and driven by data relaying cutting coordinates imparts the work piece area to be cut or engraved with sufficient thermal energy to burn away material [34]. The software provides data to the laser regarding both the type of cut to be performed and the cutting coordinates. The advantages of laser cutting to mechanical cutting are the extreme cutting precision that requires little finishing, a minimally invasive cutting path, and a small heat-affected zone that limits warping [24]. A process icon for laser cutting is shown in Figure 18. A typical laser cutter is shown in Figure 19.

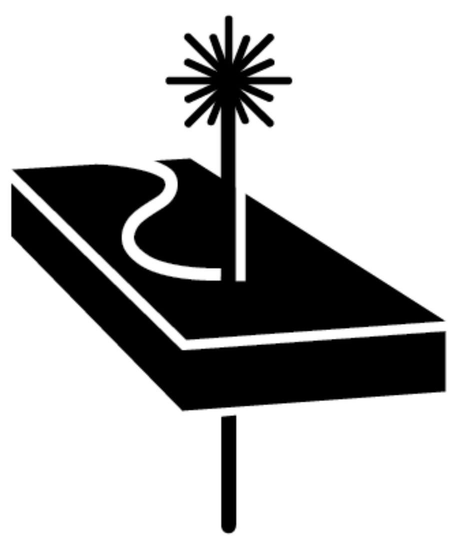

Figure 18: Laser Cutter Process Icon [24]

Figure 19: Laser Cutter [35]

Water jet cutting is a process similar to laser cutting. A work piece submerged in water is cut by a two axis water jet equipped with instructions from a program dictating cutting coordinates. A high-pressure and velocity stream of water is used to cut substrate without creating a heat-affected area, thus avoiding altering mechanical properties of the work piece. The water jet's cutting power can be augmented by impregnating the stream with an abrasive material such as alumina or garnet. Metal, stone, glass, and plastic are all common work piece materials [24]. The water jet process icon is shown in Figure 20. Figure 21 shows a new water jet cutter.

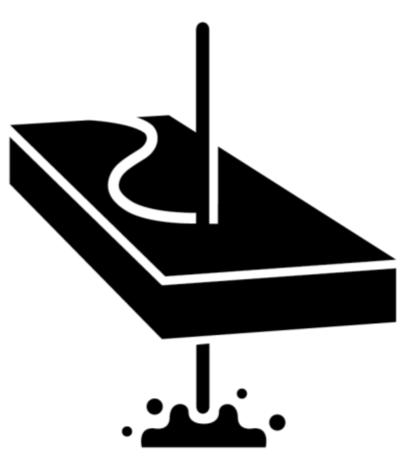

Figure 20: Water Jet Cutter Process Icon [24]

Figure 21: Water Jet Cutter [36]

Electrical Discharge Machines (EDMs) are also popular subtractive digital fabrication processes. Two different classes of EDMs that operate on similar principals exist: wire EDMs and ram EDMs. EDMs remove excess material by creating a circuit between an electrode and the work piece, which must be a conductive material. A ram EDM uses a conductive electrode, normally graphite, to remove material from the work piece by sparking away undesired material. An electrical spark jumps from the electrode to the metal work piece to burn away unwanted material; at no point does the work piece come into contact with the electrode. The EDM process takes place within a dielectric fluid that serves to circulate burned material away from the electrode and enhance the sparking process. With a ram EDM, a wire acts as the electrode and is spooled between two guides. A wire EDM is similar in some respects to a scroll saw; the work piece is fed through the taut wire, and intricate cuts or curves are easily achieved. Again, material is removed by creating a spark gap between the wire and work piece that burns away excess material. As with other subtractive processes, user-generated codes determine the tool path [24]. The process icon developed by the Graphic Design team for the ram EDM is shown in Figure 22. A ram EDM is shown in Figure 23.

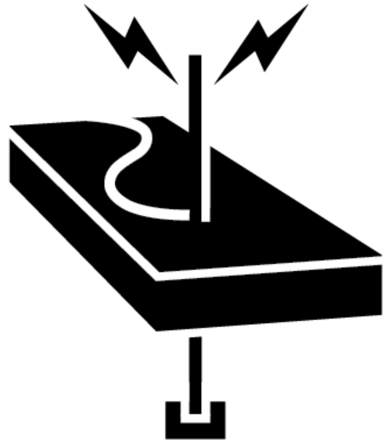

Figure 22: Ram EDM Process Icon [24]

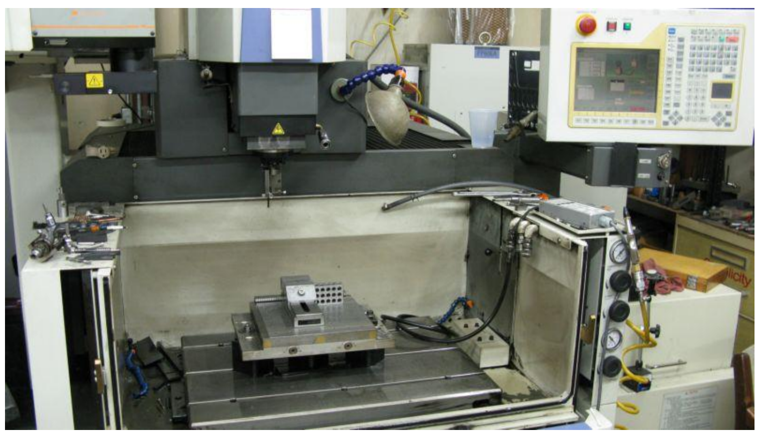

Figure 23: Ram EDM Machine [37]

3.2.3 INPUT-DRIVEN PROCESSES

Input-driven digital fabrication processes include a wide range of products capable of measuring a pre-existing product in space as well as devices that enable manipulation of virtual materials via a physical implement that mimics reality by providing haptic, or touch-based, feedback.

Coordinate measuring machines (CMMs) cover the spectrum of apparatuses that measure the dimensions of a pre-existing model. Physical contact, lasers, and white light are all commercially-used probing methods. Early CMMs utilize a physical probe to mark points in space. This process is effective as a quality assurance technique, but data collection is time-consuming and because discrete data points are marked, thorough reverse engineering is nearly impossible. Newer methods use lasers or visible light to map features of a model, and these methods can collect vast amounts of information compared to physical contact CMMs. Their only limitation is that they require a clear line of sight to acquire measurement data; features obscured by overhangs or hollow cavities cannot be measured unless there is a line of sight, and ambient light can skew results. Lasers and white light methods allow for several different images to be patched together to create a virtual solid model. As a result, laser and white light CMMs are highly effective tools for reverse engineering. A picture of a laser 3-D scanner is shown in Figure 24.

Figure 24: Optix 300 3-D Laser Scanner [38]

Digital clay carvers allow users to manipulate a virtual mass with a physical implement. These implements provide haptic feedback that resists movement of the writing implement when the user scrolls over the features of the virtual mass. Size, shape, and material characteristics of the model can be changed to suit individual needs. Haptic feedback tools are currently used in industrial design applications, the medical field (in dentistry it is used to create custom-fit insertions), animation studios, and as a troubleshooting device for patching holes or improving surface quality on solid models before sending them to a rapid prototyping machine [39].

3.3 KIOSK AND TUTORIALS

Another facet of DIGI-Net is the installation of kiosks at each on-campus fabrication center. The most recent prototype was displayed at last spring's Design Showcase and is seen at various development stages in Figure 25. Employing touch screen monitors, these kiosks give users access to a fully-functional and interactive DIGI-Net directory. The goal is for identical kiosks to be made available at a convenient location in each manufacturing facility here at Penn State so that manufacturing process information can be made readily available. Each kiosk will be equipped with the same information that is made available online, but it will be presented in a more concise fashion in a manner more conducive to the touch screen monitor interface.

The kiosk presented at the Spring 2010 Design Showcase was created for architecture and engineering courses ARCH 497A and EDSGN 497B. This model, seen in its final form in the bottom right of Figure 25, is a beta mockup of the kiosks that will be placed in different fabrication locales at Penn State. Created by both engineering and architecture students, the task was to create a stand to exhibit both the digital services of DIGI-Net and the print brochures. The students funneled a large number of alpha prototypes through a thorough survey to determine the most promising designs. Those successfully running the gauntlet were transformed into large-scale prototypes that better exposed flaws and strengths. The final kiosk – tall, slender, and elegant – was created out of matte-finished aluminum to reduce the environmental impact of the project. Aluminum can be recycled using 95% less energy than creating aluminum from raw materials [40]. The shape of the kiosk also posed safety concerns; so, calculations and experimentation was carried out that determined that the kiosk would not tip under anything less than extreme disturbance [24].

Figure 25: Design phases of the DIGI-Net Kiosk [24]

The kiosk features a number of different features that will be carried out through in future models. The DIGI-Net logo, brochure holder, touch screen, and sponsor recognition will all be a part of the final design.

Although each functional team had ownership of their part of the project and thus became culpable for its failure or success, group input was quite common. Video tutorial filming and editing went through multiple iterations; in most cases, multiple recordings were made for each tutorial. Editing of the raw video was quite significant and improved both the professional appearance of the video and its functionality. Scrolling instructions on the video tutorials highlight key portions of the instruction, and each video introduces the presenters by name and title. Text tutorials were created following the video tutorials, as the video tutorials provide a rough script for these. In all cases, most of the improvements to existing tutorials were made at group meetings by suggestions from people not directly a part of the tutorial team. These meetings served as impromptu surveys of DIGI-Net's interim success, as many of the people in the room were just as unfamiliar with digital fabrication processes as the target audience. If tutorials, process icons, or other instructions were unclear, there was immediate feedback both on what was unclear and how those problems could be mitigated. Several screenshots from the laser cutter tutorial are shown in Figure 26 and Figure 27.

Figure 26: Jamie Heilman, one of the tutorial narrators, discussing the laser cutter.

Figure 27: A close-up shot from the tutorial, featuring on-screen text instruction.

3.4 BROCHURE

The final component of DIGI-Net is a promotional brochure describing the DIGI-Net project. These brochures, distributed at events and available at each kiosk location, are intended to be both informative and persuasive, as the end goal is to raise awareness for fundraising needs and provide examples of previous projects that may serve as inspiration to budding designers. The Graphic Design team has been instrumental in determining the aesthetics of these brochures. Inks, paper, font type and size, color schemes, motifs, binding, map icons, and potential DIGI-Net logos were all evaluated or created by a team of Graphic Design faculty and students. Graphic design elements present in and created for the brochure are the common bond between all DIGI-Net productions. In the hopes of developing an instantly recognizable brand, DIGI-Net has maintained the same logo, font, color scheme, and process icons across all project lines. Several pages from the DIGI-Net brochure are shown in Figure 28.

Figure 28: Brochure Samples [24]

3.5 SUMMARY

The array of digital fabrication tools made available to the Penn State community makes the physical realization of an almost infinite number of product ideas and concepts possible. Additive, subtractive, and input-driven fabrication techniques at Penn State ensure that accurate models can be constructed out of a number of different materials almost as quickly as they were conceived. These tools provide the basis for the DIGI-Net project. Inspired by the creativity and innovation that digital fabrication tools bring about, DIGI-Net seeks to encourage usage of these tools by provisioning instruction manuals, contact information, video tutorials, an interactive database, and on-site kiosks.

The majority of digital fabrication resources at Penn State are found at either the Learning Factory, FAME Lab, or in the Stuckeman Family Building. Providing information on these tools democratizes the digital fabrication processes that have proven so useful. DIGI-Net is Penn State's response to tools such as Fab@Home and RepRap; the more people who can use rapid prototyping tools to create useful goods, the better. Group meetings, best described as loosely-administered open forums, have proven conducive to making improvements on existing products as the multidisciplinary group comprising DIGI-Net has a variety of different knowledge bases. The functional teams, which set out to complete tasks prior to the April 2010 Design Showcase, worked on sub-projects such as a cohesive website, searchable database, video and text tutorial set, process icons, and model kiosk.

So what made the DIGI-Net teams unique from those created for other academic projects? Each team represented a diverse group of individuals with different disciplinary skillsets in different stages of their education. The tutorials team, for instance, was comprised of two Mechanical Engineering students and an Architecture student, and was informally led by the Architecture student. These teams were exposed on a biweekly basis to the critiques of others; both those familiar and unfamiliar with previously completed work were able and willing to provide their insights, questions, and concerns. It was not uncommon to hear a Graphic Design student question the proposed features of the website or a Graphic Design professor ask about the purpose of a particular tutorial module.

The next chapter performs a post-mortem on what has been accomplished by DIGI-Net to date. Although there was a definite sense of finality provided by the spring Showcase, this project is ongoing and discussions with project administrators as well as personal opinions shed light on what was accomplished and what was not are addressed.

CHAPTER 4

ANALYSIS OF DIGI-NET DEVELOPMENT

The Design Showcase in April 2010 was the first public unveiling of most of DIGI-Net's features. Starting in the Fall 2009 semester, the DIGI-Net team partitioned into different functional teams as discussed in Chapter 3 to accomplish the various sub-projects DIGI-Net entails. Given such a strict deadline, team members had to be able to work within time constraints and adjust to problems that arose as the project progressed. Significant strides were made to roll out an appealing line of services that could be pitched to faculty, corporate sponsors, and students. Many internal goals of this project were met or exceeded, while others were not, but along the way all of the functional groups encountered challenges, roadblocks, or came to unexpected conclusions.

4.1 WHAT WORKED

Many parts of DIGI-Net's self-expressed framework were on full display at the April 2010 Design Showcase. The kiosk, equipped with a functioning touch screen monitor interface linked to the DIGI-Net website and print brochures, displayed most of DIGI-Net's capabilities. This project resulted in fruitful interdisciplinary work, which was one of the desired offshoots of creating functional teams. The goal of interdisciplinary work is not to "build on methods and insights from existing disciplines … [but] to interpenetrate disciplines, changing what they do by providing communicative forms and channels for renegotiating disciplinary boundaries and generating new epistemic standards" [38]. The cross-talk between disciplines and functional teams is exactly what has allowed DIGI-Net to flourish. A member of the Graphic Design team does not take cues from someone with a

Mechanical Engineering background because it will allow them to deepen their knowledge of Graphic Design, but because it can broaden their experiences as a Graphic Designer. The difference may seem to be in semantics, but the true goal of interdisciplinary work is not so much to deepen one's understanding of their topic of expertise but rather to broaden their knowledge base of a number of different topics with which they may not be familiar. In every memorable instance of interdisciplinary work by DIGI-Net, there was some positive quality as a result of that interaction. Although there were times when different disciplinary backgrounds caused conflict, those conflicts sparked constructive feedback, thoughtful conversation, and a digression from the stasis that occasionally stifles original thought.

Another aspect of DIGI-Net that made the project largely successful at the Design Showcase was the cohesion exhibited between different functional teams. Work from one team flowed fairly seamlessly into what other teams did. Each and every media form incorporated common graphic design elements such as color schemes, process icons, and logos. Video tutorials, originally shot in high definition to maximize video quality should they be converted to DVDs, were adapted to a lower quality so as to best stream online without losing resolution. During the spring, group meetings ensured not only that everyone was on task, but that each sub-project would, upon completion, converge seamlessly onto the same singularity. To that end, the kiosk team had the kiosk manufactured to incorporate the DIGI-Net logo, using digital fabrication tools to do so, no less. The website maintained a consistent look between pages with help from the Graphic Design team, and brochures were printed concisely describing both the DIGI-Net project and the basics of many of the digital fabrication tools discussed in the text and video tutorials.

4.2 WHAT NEEDED IMPROVEMENT

For all of DIGI-Net's success, there was much room for improvement. A problem faced to some extent in DIGI-Net and in many multidisciplinary teams, was effective communication. ANGEL, Penn State's course management website, was used to set up a group for DIGI-Net. Central communication took place through this client, but functional teams largely relied on their normal email client (webmail, Gmail, etc.) for communication within teams. This disparity in modes of communication meant that sometimes, information would get lost or misplaced. Additionally, communication between meetings was sparse. Meeting times were mentioned at the previous meeting and reiterated one or two days before they were set to take place, but attendance was occasionally just a motley crew of core team members. Initially, there were communication deficiencies within meetings, and effectively explaining digital fabrication processes to people who have never encountered these tools is a difficult procedure. The inclusion of people never exposed to digital fabrication was of great benefit to the tutorials team, as their feedback made it possible to create tutorials with clear explanations of initially unclear machines.

One result of unclear communication was the initial lack of established goals and deadlines. When it became clear that some teams were not effectively meeting internal deadlines, weekly progress reports, milestones, and firm deadlines were set for various aspects of the project. With these measures in place, most teams were able to accomplish their tasks on time. Nonetheless, struggles with technology tended to be a driving factor in whether or not deadlines were met

4.3 ROADBLOCKS ENCOUNTERED

As mentioned before, once firm deadlines and weekly progress reports became integrated into DIGI-Net's core tasks, milestones were met more consistently. However, the technology driving and allowing DIGI-Net to exist often caused hiccups that could not be addressed in time to meet deadlines. The tutorial team in particular ran into numerous problems. On several occasions, videos were shot in a format that could not be edited in Apple's Final Cut Pro software. These had to be reshot, which required getting fabrication staff to commit to a block of time during which they were available to reshoot; this is not an easy task during most of the academic year because their priorities lie in solving problems for students actually using the fabrication tools. Other problems arose with PC and Mac compatibility for the video tutorial team, and these problems contributed to several other delays. In the end, the video tutorial team was able to create four final draft tutorials that could be displayed at the Design Showcase, and while this seems acceptable for display purposes, the initial goal was to film all of the video tutorials.

Problems were not limited to just the tutorial team. PHP, the language used to code the website, was not adopted until part of the website architecture had already been determined. The IST team was slow to adapt to using PHP, and there were some problems with getting the website and database to properly interact. The database also faced coding issues. MySQL was used to create the final version of the page, but at first SQLite, another database system was used. The conversion from SQLite to MySQL created another delay; this was fortunately overcome before the Design Showcase.

As a result of delays on the parts of the tutorial and database, the website was slow to take shape. Once created, it faced a set of compatibility issues with the kiosk. The monitor purchased for the kiosk, an HP touch screen, did not interact well with Windows 7 Operating System, which was used to launch the website. For the first hour of the Design Showcase, the IST team worked to rectify touch screen functionality and web site operability.

A lack of centralized information also created difficult hurdles at times. The size of video files, website data, and other information, as well as the use of functional teams meant that oftentimes information was kept in separate locations. Penn State's U-Drive, not easily accessed on all campus computers, is not equipped with enough personal space to accommodate all of the files created by the video tutorial team, so this information was stored on an external hard drive. Had a central information bank been created, files from other teams could have been accessed readily and used for cross-referencing information.

4.4 OVERALL RESULTS

The overall process, reflected at the spring Design Showcase, was highly beneficial to involved team members. This project demonstrated the benefits of interdisciplinary work and gave most team members experiences with new technologies, coding languages, and software. The end result is a set of process icons, website architecture, a database, kiosk, brochure, and four sets of video tutorials. Although the project has not been run to completion, the work displayed at the Design Showcase was sufficiently demonstrative of DIGI-Net's final goals that Penn State administrators have pledged to fund the project more aggressively in the future, which will enable the project to cull more resources and create a fully functional set of services without sacrificing quality.

4.5 SUMMARY

DIGI-Net accomplished most of what it set out to do by April 2010. Not all of the tutorials were finished in time for the Design Showcase, but the four tutorials that were finished demonstrated how the suite of text and video tutorials would work. The website was also not completely polished; again, the main functions of the website worked – an interactive database successfully led users to a set of machines and training tutorials that could meet their manufacturing needs. The Graphic Design team finished all of the tasks given to them, which included creating a set of process icons, color schemes, and font and color selection. The Design Showcase led to further funding, which will allow DIGI-Net to exist in the future; there will be many kinks to fix in future iterations of this project. Technology may continue to be problematic as it is tested, but many challenges with technology have been overcome over the course of the project to date.

The next chapter details future recommendations for DIGI-Net as it moves forward. Some of these recommendations are extensions of the work that has already been completed; other suggestions provide enlightening insights into the issues DIGI-Net faces and potential ways to tackle those problems.

CHAPTER 5

CONTRIBUTIONS AND FUTURE RECOMMENDATIONS FOR DIGI-NET

5.1 RESEARCH CONTRIBUTIONS

Digital fabrication, or the use of hardware and software to translate between virtual models and physical forms, has enormous power. Digital fabrication processes can be used to reverse engineer existing products, deliver precision-machined components for custom assemblies, or prototype artistic and functional models of emerging product designs. These processes can be divided into additive processes that deliver parts from scratch, subtractive processes that manipulate or modify a pre-existing work piece to arrive at a final form, or input-driven processes that either deliver the spatial coordinates of an existing part or permit users to associate a realistic tactile feel with virtual parts being designed on a computer.

Fortunately, Penn State possesses machinery capable of performing a number of additive, subtractive, and input-driven digital fabrication processes. These tools are a fantastic resource for students, faculty, and staff alike. Quick mockups and prototypes are common drivers of innovation; universities such as Penn State must foster an environment complete with these tools to maintain an image of being a hotbed for cutting-edge thinking. Nevertheless, there are far too many barriers to innovation at on-campus fabrication sites. Equipment at Penn State is rarely regarded as a common resource to be shared between colleges. Disparities in hours of operation, methods of payment, location, required certifications, and training have constricted the flow of information between people of different academic backgrounds, skill sets, and levels of experience. Awareness of fabrication tools located outside of one's college is oftentimes paper-thin.

DIGI-Net seeks to open lines of communication at Penn State between colleges in order to provide students and faculty with up-to-date, interactive, and informative tools to assist in projects requiring digital fabrication machinery. This mission will be accomplished through standalone kiosks, printed case studies, online safety certification and instructional tutorials, and an updatable database populated by information regarding machinery specifics. DIGI-Net is run by a multidisciplinary group that hopes to stimulate innovation at Penn State by increasing collaboration between people of disparate disciplines. As a result, there is representation in DIGI-Net teams from the College of Engineering, College of Arts and Architecture, and College of Information Sciences and Technology.

It is DIGI-Net's firm belief that increasing academic cross-talk will have enormous benefit for individuals taking advantage of our services as well as to Penn State and its corporate associates. Opening students to information that shapes how manufacturing projects are managed and completed will create a "water cooler" effect at several sites on campus that should lead to the dissemination of powerful information between engineering, design, architectural, and manufacturing disciplines. Collaborative efforts resulting in diverse teams are projected to produce a broad array of designs from which an optimal solution for almost any problem can be culled.

Although the most recent wave of funding from Penn State administrators is a vote of confidence for the current direction of DIGI-Net, there are several ways to improve upon what already exists. As discussed in the previous chapter, an ability to embrace new technologies, software, and disseminate important information to DIGI-Net members was a problem with some functional teams. Future groups within DIGI-Net must manage issues concerning technology within the timeframes established for deadlines, and information needs to be distributed effectively to all group members in order to reach the full potential of this project.

So far, DIGI-Net has contributed significantly to its objectives. All digital manufacturing tools, located in ten different buildings have been identified and collated in the database. An effective classification scheme dividing resources into additive, subtractive, or input-based has been implemented. Process descriptions have been created to accompany all of the digital fabrication tools, and process icons have been developed for 19 different processes. Video and text tutorials have been created for the powder based printers, laser cutters, CNC router, and water jet cutter. A website searchable by process, machine type, and facility has been created. A kiosk with a touch screen that runs all of DIGI-Net's digital content has been fabricated. Finally, a print brochure summarizing six different interdisciplinary projects utilizing digital fabrication tools and Penn State's resources was printed for distribution.

5.2 LIMITATIONS AND ORGANIZATIONAL IMPROVEMENTS

The most glaring issue with team preparation for the spring Design Showcase was the willingness to meet internal deadlines. Although most of these problems were related to unforeseen technological challenges, teams will need to build a significant amount of buffer time into their planning so that they can create more realistically achievable goals and milestones. Meeting deadlines in project teams is not an uncommon problem; according to one study, "half of all system and technology implementation projects overrun their budgets and schedules by 200% or more" [41]. Although DIGI-Net is not in the same type of competitive markets where a late product launch can drown a company, there are still many negative consequences of missing deadlines. Perpetually missing these stated dates could reduce donor confidence in the project, frustrate team members and reduce overall morale, or leave the door open for other project groups to complete similar work.

The two main causes of missing deadlines identified in many reports are improper group pacing and indecision as to how best allocate time to execute sub-tasks. These effects are especially pronounced in multidisciplinary teams where there often exist large disparities in how temporal constraints are perceived [41]. Many of these problems encountered on multidisciplinary teams can be ameliorated by establishing a set of temporal strategies that congeal different team members' perceptions of how deadlines should be handled. An effective temporal strategy is one that includes information not only on the actual deadline, but how work is distributed and how quickly sub-tasks need to be completed. Most importantly, an effective strategy is one where all team members buy into the concept and self-evaluate on a regular basis to ensure that the overall goals are being met.

Three main methods are used to construct a realistic temporal strategy: planning, reminders, and reflexivity. Planning, the initial stage, requires team members to allocate an accurate, realistic amount of time to each task and then assess which team members should work on particular tasks. Reminders can cover any number of tools: Gantt charts, interim progress reports, team meetings, and infrequent pressure from other team members may serve to imply urgency that is conducive to meeting these deadlines. Reflexivity is achieved through extensive self-evaluation of objectives. Teams that take time to review the overall scope of the project, identify their own objectives, and consider how their objectives fit with the overall project criteria meet deadlines far more consistently than those that compartmentalize their work and isolate themselves from their peers [41]. Implementation of temporal strategies, and more importantly, sticking to those strategies throughout the course of the project will likely result in a higher quality of work and a higher amount of work accomplished in the prescribed amount of time.

Another element crucial to the continued success of DIGI-Net is the effective distribution of information. This is important on several organizational levels of DIGI-Net. Between team members, there exists a need to cooperate and provide a support system for each other. A central data bank for teams would alleviate some of the pressures of transferring the latest version of files between members of each team. Between group leaders and team members, it is important to make the innovation strategy completely transparent and "balance the creative needs of the design team[s] against the need for certainty and control of the business" [42]. The managerial strategy for DIGI-Net should be to inform teams as much as possible and ensure that they have stake in the success of the entire group. Thus far, these qualities have been exuded by team leaders; it must continue to achieve results.

Decentralized management, utilized by DIGI-Net, requires a large component of political skill. One director of a multidisciplinary team at another university "believed that 'the directorship works better when there is a sense that is beyond obligation or duty,' calling this force 'a passionate commitment to the topic.' Another director noted that a certain 'public spiritedness' along with a 'consistency of vision' provide 'critical' ingredients for launching cross-school initiatives" [43]. Through its use of several faculty members as team leaders, DIGI-Net ensures that there are points of contact in each college for functional teams to contact, and thus far, there has been great consistency between the stated goals and expectations of faculty members, which must continue to achieve cohesive design. Most mature research and design groups at universities use a committee approach to make decisions; this strategy has been linked to a program's staying power [43].

5.3 FUTURE WORK

Although DIGI-Net's success can to some measure be determined by how well different functional teams accomplish their goals, meet deadlines, and interact with other functional teams, the real measure of success is how the Penn State community reacts to the services provided by DIGI-Net. How can the usage of DIGI-Net be measured, and how can the expected increase in demand for digital fabrication tools be managed?

One way to measure the usefulness of DIGI-Net is to install card swipes at entrances to Penn State's fabrication centers. These PSU ID+ card swipe stations would not only count the total number of people using machinery, but also the distribution of majors within that population. This data could be used to paint a picture of how much interaction was taking place as a result of DIGI-Net's efforts. Similar measures can also be implemented in the digital content of DIGI-Net. Although the content should remain accessible to anyone, the website could include a log-in page to Penn State's WebAccess that also records statistics on the number of unique users, the number of times a particular user visits the page, and what a particular user's major is. To entice users to log-in on an optional page, additional content linking the DIGI-Net website to ANGEL, Webmail, or E-Lion could be made available to only Penn State users.

The projected increase in usage of resources raises a number of questions, not all of which have answers. For instance, how should equipment usage be prioritized? In the event that a machine has a queue of interested users, is priority given to people who belong to the academic college or department that own that particular resource? Is priority given based on a number of popular dispatching methods, such as First In-First Out (FIFO), Shortest

Process Time (SPT), or Earliest Due Date (EDD)? Additionally, how will interested parties pay to partake in using Penn State's equipment? The Learning Factory and FAME Lab are partially financed through university allocations and the FAME Lab is also funded through a student technology fee while the Learning Factory is funded by corporate sponsors. Usage of some equipment is limited to a certain build volume, after which students must pay for material. The Stuckeman Family Building equipment requires students to pay for their own raw materials, and a printing fee is charged for use of their equipment. Right now, these are not burgeoning problems because the people using Engineering tools are all members of the College of Engineering, and people using the tools of the College of Arts and Architecture are respectively, art and architecture majors. This financial quandary becomes significantly more muddled when people begin to use equipment from different colleges. All of these questions need to be answered if and when utilization of digital fabrication processes expands beyond just the primary engineering, architecture, and arts groups of Penn State's current design community.

APPENDIX A: MACHINE LISTING TABLE

TABLE A-1: Full Machine Listing Database

Machine Name	Manufacturer	Materials	Material Limits	Process	Classification	Location	Contact	E-mail	Hours
VF2 Vertical CNC Mill	Haas	Metals, Plastics	30" X 16" X 20"	CNC Mill	Subtractive	FAME Lab - Leonhard	Mike Immel	mci101@psu.edu	8A-5P M-F
VF2 Vertical CNC Mill	Haas	Metals, Plastics	30" X 16" X 20"	CNC Mill	Subtractive	FAME Lab - Leonhard	Mike Immel	mci101@psu.edu	8A-5P M-F
VM3 Vertical CNC Mill	Haas	Metals, Plastics	40" X 26" X 25"	CNC Mill	Subtractive	FAME Lab - Leonhard	Mike Immel	mci101@psu.edu	8A-5P M-F
VF2 Vertical CNC Mill	Haas	Metals, Plastics	30" X 16" X 20"	CNC Mill	Subtractive	FAME Lab - Leonhard	Mike Immel	mci101@psu.edu	8A-5P M-F
VF0 Vertical CNC Mill	Haas	Metals, Plastics	20" X 16" X 20"	CNC Mill	Subtractive	FAME Lab - Leonhard	Mike Immel	mci101@psu.edu	8A-5P M-F
VF0 Vertical CNC Mill	Haas	Metals, Plastics	20" X 16" X 20"	CNC Mill	Subtractive	FAME Lab - Leonhard	Mike Immel	mci101@psu.edu	8A-5P M-F
SL20T CNC Lathe	Haas	Metals, Plastics	262 X 508 turn cap., 211mm chuck	CNC Lathe	Subtractive	FAME Lab - Leonhard	Mike Immel	mci101@psu.edu	8A-5P M-F
SL30T CNC Lathe	Haas	Metals, Plastics	432 X 864mm turn cap., 254mm chuck	CNC Lathe	Subtractive	FAME Lab - Leonhard	Mike Immel	mci101@psu.edu	8A-5P M-F
SL20 CNC Lathe	Haas	Metals, Plastics	262 X 508 turn cap., 211mm chuck	CNC Lathe	Subtractive	FAME Lab - Leonhard	Mike Immel	mci101@psu.edu	8A-5P M-F
SL20 CNC Lathe	Haas	Metals, Plastics	262 X 508 turn cap., 211mm chuck	CNC Lathe	Subtractive	FAME Lab - Leonhard	Mike Immel	mci101@psu.edu	8A-5P M-F
SL20T CNC Lathe	Haas	Metals, Plastics	262 X 508 turn cap., 211mm chuck	CNC Lathe	Subtractive	FAME Lab - Leonhard	Mike Immel	mci101@psu.edu	8A-5P M-F
Dimension 1200 FDM	Stratasys	ABS Plastic	10"X10"X12"	Fused Deposition Modeling	Additive	FAME Lab - Leonhard	Mike Immel	mci101@psu.edu	8A-5P M-F
Wire EDM	NA	Conductive Metals	12"X12"	Wire EDM	Subtractive	FAME Lab - Leonhard	Mike Immel	mci101@psu.edu	8A-5P M-F
RAM EDM	NA	Conductive Metals	8"X8"	RAM EDM	Subtractive	FAME Lab - Leonhard	Mike Immel	mci101@psu.edu	8A-5P M-F
FDM 2000	Stratasys	ABS Plastic	10"X10"X10"	Fused Deposition Modeling	Additive	Learning Factory	Carson Baird	cxb290@psu.edu	8A-10P M-F
3D Printer	Allegheny Systems	Plaster	20"X10"X10"	Fused Deposition Modeling	Additive	Learning Factory	Carson Baird	cxb290@psu.edu	8A-10P M-F
EZ-Trak CNC/Manual Vertical Mill	Bridgeport	Metals, Plastics	30"X20"X20"	CNC Mill	Subtractive	Learning Factory	Carson Baird	cxb290@psu.edu	8A-10P M-F
Waterjet	OMax	Metals, Plastics, Fabrics	36"X24"	Waterjet	Subtractive	Learning Factory	Carson Baird	cxb290@psu.edu	8A-10P M-F

CNC Router 9100 Series	Precix	Wood, Paper, Plaster, Metal, Foam	49"X98"	CNC Router	Subtractive	13 Stuckeman	Jamie Heilman	jamieheilman@psu.edu	M-R: 9A-9:30P; F: 9A-5P; Sun: 1P-9:30P
Zcorp 310 plus	z corporation	Plaster	8"X10"X8"	Powder Bed Printing	Additive	13 Stuckeman	Jamie Heilman	jamieheilman@psu.edu	M-R: 9A-9:30P; F: 9A-5P; Sun: 1P-9:30P
CNC Lathe	Clausing Colchester	Plastics, Metals	15" swing - 9" over cross slide, 36" chuck	CNC Lathe	Subtractive	25 Reber	Phil Irwin	pei1@psu.edu	8A-4:30P M-F
TM1 Vertical CNC Mill	Haas	Plastics, Metals	30"X12"X16"	CNC Mill	Subtractive	25 Reber	Larry Millinder	lom102@psu.edu	8A-4:30P M-F
CNC MIll	Bridgeport	Plaster, Plastics, Metal	10" swing, +/- 20 degree tilt, 4.5"on Z axis	CNC Mill	Subtractive	25 Reber	Phil Irwin	pei1@psu.edu	8A-4:30P M-F
CNC Mill	Mill Port Centroid	Plaster, Plastics, Metal	40"X15"X33"	CNC Mill	Subtractive	25 Reber	Phil Irwin	pei1@psu.edu	8A-4:30P M-F
Carvewright Woodcarver	Carvewright	Wood, Paper	14.5" X 5" high	CNC Router	Subtractive	23 Reber	Larry Millinder	lom102@psu.edu	8A-4:30P M-F
Desktop 3D Scanner	Next Engine		13.5" tall X 10.1" wide	Digital Scanner	Input	315 Hammond	Wescott Pusey	wpusey@engr.psu.edu	7:30A-4P M-F
Optix 400 3D Laser Scanner	3D Digital Corp.		8"X12" single scan	Digital Scanner	Input	315 Hammond	Wescott Pusey	wpusey@engr.psu.edu	7:30A-4P M-F
CNC Printer Circuit Board Cutter	T-Tech, Inc.	Copper Only	16"X12"X max 30/1000"	CNC Circuit Board Cutter	Subtractive	315 Hammond	Wescott Pusey	wpusey@engr.psu.edu	7:30A-4P M-F
LC Series 3024 CNC Router	Techno Inc.	Plastic, Wood, Foam	2 1/2" wide sheets	CNC Router	Subtractive	108 Visual Arts	Jerry Bierley		8A-9P M-F
Laser Cutter X-660	Universal Laser Systems Inc	Wood, Fabric, Glass, Marble, Slate, Acrylic	18"X32" cutting bed	Laser Cutter	Subtractive	408 Stuckeman	Jamie Heilman	jamieheilman@psu.edu	M-R: 9A-9:30P; F: 9A-5P; Sun: 1P-9:30P
ZCorp 310 Plus	Z Corporation	Plaster	10" X9"X12"	Powder Bed Printing	Additive	313 Hammond	Wescott Pusey	wpusey@engr.psu.edu	7:30A-4P M-F

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The Pennsylvania State University
Bachelor of Science in Industrial Engineering
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Honors in Industrial Engineering and Mechanical Engineering, Schreyer Honors College
Thesis Title: *The Development of DIGI-Net at the Pennsylvania State University to Support Interdisciplinary Innovation*
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Work Experience
Mechanical Engineering Intern
Harsco Corporation
Summer 2010
- Introduced testing methods and oversaw product analysis for automated sorting equipment
- Designed troubleshooting solutions for wet-dressing steel slag recycling and pelletizing plant

Product Engineering Intern
Alcoa Howmet Castings
Summer 2009
- Led and executed projects that improved product quality by using Six Sigma methods
- Designed and implemented solutions to eliminate or reduce internal product defects

Quality Engineering Intern
ArcelorMittal
Summer 2008
- Streamlined two cold mill lines through several projects analyzing productivity metrics resulting in savings of $1,000,000 per year across all product lines

Honors and Awards
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