Development of an Automated Manufacturing Course with Lab for Undergraduates

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***Abstract*— Many engineering programs at universities across the country have dropped machine shop and manufacturing courses from their curriculum due to budget constraints, accreditation requirements, and concerns about student safety. At the University of Portland, we have resurrected and enhanced a hands-on advanced CAD and automated manufacturing course that introduces students to advanced solid modeling techniques in CAD, such as sweeps, lofts, and surfacing methods. In addition, students learn manual machining and vacuum forming in our machine shop, along with learning how to create tool paths for CNC machining their designed CAD parts out of wax on various three axis end mills, a 3D printer, and a 3D laser scanner. The end mills were all refurbished and/or repaired over a period of four years to get this course up and running. A commercial software package, MasterCAM, was used in conjunction with SolidWorks as the platform from which to learn about automated manufacturing. In addition, a MakerBot 3D printer was built from a kit to give students experience with future manufacturing techniques. The 3D laser scanner was student designed and built and creates CAD surface models of parts, useful for learning about reverse engineering. The machinable wax used for machining is recycled, melted down, and formed into blocks again for reuse. This saves considerable money. Our goal has been to enhance design quality in our curriculum through experiential learning. Prior to taking this course, all mechanical engineering students are required to take a solid modeling CAD course to learn the basics. However, our experience has been that students do not conceptually understand the importance of designing for manufacture. Although emphasized in all courses, without the hands-on experience, it is difficult for students to remember to apply fillet radii to the bottom of pockets, for example. When faced with having to fit a block with sharp corners into a machined pocket with its default small corner radii, however, learning is instantaneous. The early outcomes of this course show students have learned a great deal about design for manufacturing and manufacturing techniques from taking this course.**

Keywords- experiential learning, manufacturing, NC machining, hands-on laboratory experiments, undergraduate engineering, 3D printing, rapid prototyping, MasterCAM, SolidWorks

I. Introduction

This article covers the reintroduction last year of an automated manufacturing course in the mechanical engineering department at the University of Portland. This course existed for many years, but faded away in 2000 after the instructor retired and the small end mill used for the course stopped functioning. Over the past four years, it has been my goal to revitalize this course and begin offering it again. The new and improved version of this course will now be offered every year.

Why offer an advanced CAD and automated manufacturing course? It has safety risks, equipment purchase, maintenance, and refurbishment costs, and requires a large investment of time and faculty resources to provide a lab-based course to a couple dozen students. The reasons are numerous, but mainly hinge around the fact that the demographic of our engineering student body has changed, and the vast majority of our students have had no exposure to or use of manufacturing equipment of any kind. Since the early 1980s, two-thirds or more of high schools nationwide have eliminated their technical education classes [1], mechanical and electronic devices have become too complex for the average teenager to work on [1], and many colleges have had to eliminate lab courses due to budget constraints. Engineering students frequently graduate with little hands-on, experiential learning, and there is a “disconnect [and] engineering students are not adequately prepared, in [industry’s] view, to enter today’s workforce” [2]. Also, the world of manufacturing is changing, and engineers of the future will need to be able to work with new equipment, technologies, and manufacturing techniques. Awareness of these techniques will be key to their professional development and success as engineers [3].

The need to shift from scientific inquiry to engineering design has been addressed by the Next Generation Science Standards, as being critical for our students [4]. The core concepts they want students to acquire are achieved through the experiential learning we have implemented:

1. Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants.

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2. Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.

3. Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics as well as possible social, cultural, and environmental impacts.

4. Use a computer simulation to model the impact of proposed solutions to a complex real-world problem with numerous criteria and constraints on interactions within and between systems relevant to the problem.

The National Research Council of the National Academies has also been involved in revising our K-12 science education, and they are also focusing on integrating scientific inquiry with the skills of engineering practice [5]. They have stressed that a narrow focus on conceptually teaching science has led to the unfortunate consequence of students believing science is a body of isolated facts. By integrating the knowledge of a science with skills simultaneously, students' minds are cultivated to be able to engage in scientific and engineering inquiry.

This type of experiential learning needs to be carried forth into the college level. In another National Research Council publication, "Promising Practices in Undergraduate Science, Technology, Engineering, and Mathematics Education: Summary of Two Workshops", the authors found that some of the strongest predictors of success were in-class activities that actively engaged students in the learning [6]. They found notable success when students were involved in problem-based learning, beginning with a problem to be solved, followed by some content delivery of theory, skills, or case studies, followed by small group activities, and completed by designing a solution.

At our university, we have noticed that students often make "manufacturing errors" in their CAD solid models, such as neglecting to put fillets in the bottoms of holes. This is due to their ignorance of manufacturing tools and how they are used. "The disappearance of tools from our common education is the first step toward a wider ignorance of the world of artifacts we inhabit" [1]. It is difficult, if not impossible, for us to explain why such things as fillets are required on their designs, since they have no context to understand what we are saying. We feel this points to an underlying weakness in problem solving among our students, as the vast majority of our curriculum uses textbooks with "answers" in the back of the text. This problem persists all the way into our senior design capstone sequence, where students produce beautiful CAD models and assemblies that cannot be manufactured or assembled. Thus, we have embarked on a strategic plan to increase the amount of design and experiential learning in our mechanical engineering curriculum.

The redesigned advanced CAD and automated manufacturing course is intended to provide hands-on experiential learning through a variety of equipment and software tools. The lab now contains four end mills, all three axis, a 3D laser scanner for reverse engineering, and a small 3D printer. Additionally, student teams have lab rotations through the machine shop to learn manual machining, vacuum forming, and molding techniques. The remainder of this paper discusses all of the course curricula in detail, the equipment and how it was refurbished, the costs of establishing this course, and the outcomes achieved.

II. Lab Equipment Details

All our mechanical engineering students are required to take an introductory course in engineering graphics, which includes the use of SolidWorks®. This knowledge is used in follow-on classes, such as finite element analysis (also required), a balsawood bridge design competition, and in senior design. Students coming into the advanced CAD and automated manufacturing course have this background in CAD, which is used as a basis to begin the instruction with the introduction of new software, MasterCAM for SolidWorks®. This new product offering by MasterCAM is an add-in module embedded within the graphical user interface of SolidWorks®. Thus, it is easy for students to adapt to the increased functionality, and they are comfortable switching between modes to edit or adjust dimensions on their CAD models, and then return to their tool path model. MasterCAM® allows the students to embed their CAD model in a block of material and then machine away the excess until the CAD model is again revealed. For 2012, we used SolidWorks 2012 (Educational edition) and MasterCAM X6. We upgrade to the latest revision of all software every year.

The CAD and CAM modeling was taught in a computer classroom that contained 35 Windows 7 workstations with enhanced graphics cards and 21 inch LCD monitors. The textbook used for the MasterCAM was "MasterCAM for SolidWorks X6" by In-House Solutions. The text came with all the CAD models to do the exercises in all 13 chapters, but to improve the students' CAD skills, I had them make all their own models and only provided the models for classroom exercises. The chapters were very thorough, perhaps too complete, as the students could follow step-by-step to create their tool paths. However, all the lab rotations were open-ended designs that the students developed themselves, and they had to then create their own tool paths from scratch.

Lectures in the computer classroom were one day per week, and labs were the other day each week. The first five lecture periods were devoted to learning MasterCAM and refreshing CAD skills by building the models for the exercises. The next eight lecture periods were devoted to learning advanced techniques in SolidWorks. As there are no good textbooks on SolidWorks, I worked with my local software distributor (MCAD in Beaverton, Oregon) to obtain a couple of their instructional course books. These were outdated by one revision, 2011, but they allowed me to copy, paste, and combine them in any way I wished to make an instructional course pack. I pulled mainly from their

"SolidWorks Advanced Part Modeling" and "Surface Modeling" books. As I did not have any of the referenced models, and the books were meant to be used with instructor guidance, there were many challenges with the course pack I created. However, we were able to cover many advanced topics, including sweeps, lofts, and surfaces.

On lab days, the students had two weeks at each of six stations. During the first lab period, students would read the various equipment tutorials I had prepared and dry run through the entire set up procedure. Then, they would build their own model and machine it the following week. As the semester progressed and the students got more enthused about what they could do, the time to machine their models increased, so the students often came back on their own time (in pairs) and finished their machining.

For the lab, I utilized machinable wax. There were a number of wax blocks available from the prior course in 2000, and a crock pot and aluminum mold that had been made into a wax recycling system. The machinable wax blocks were 3 inches by 6 inches by 1.5 inches thick, and new ones cost about six dollars each to purchase. So, we utilized the wax recycling system to melt down all the stored shavings and discarded projects into new blocks. The color was muddied from blue or purple to a brownish purple at first, as the stored shavings had bits of plastic and other debris. When collecting the shavings from the new blocks, we purchased a clean shop vacuum that attached to a five gallon bucket. We used only that bucket for the new blocks, and they molded into serviceable and nicely colored new blocks.

The lab contains four end mills, a 3D laser scanner, and a 3D printer. In addition, the machine shop contains a manual end mill and a vacuum forming machine. Each of these pieces of equipment will be discussed below, including when it was purchased, how it was refurbished, and its capabilities.

A. EMCO PC-50 Mill by Maier Industries

This small, tabletop three-axis mill was purchased in the 1990s for the original automated manufacturing class. It was purchased without the onboard controller and instead used a Windows 98 and DOS-based software interface. My predecessor had determined that a couple of the cards in the EMCO were faulty and had purchased replacement cards. I had those installed, but could not get the computer to run. It turns out that someone had inadvertently disposed of the Windows 98 computer that served as the controller. Fortunately, they had removed the ISA card first. According to Maier, the Windows 98 environment cannot be emulated, so I had to locate another Windows 98 computer that had an ISA slot. Most Windows 98 computers used PCI slots, so it was challenging, but I finally managed to locate one that met my needs. The MasterCAM software would not run on this computer, however, so a Windows 7 computer was also needed. To transfer files, we use the CD Read/Write drive, as the Windows 98 computer cannot read a USB drive. All of this could be overcome by refurbishing the EMCO with a new controller, but that would cost $6000. It is slated for refurbishment sometime in the next three years, depending on other lab needs. The EMCO itself machines beautifully and produces high quality parts in wax, plastic, and aluminum. It is a very safe machine that will only operate when the door is closed, and it will stop itself rather than exceed a safe travel limit. There are many of these EMCO PC-50 mills around, and they are a low cost way to start an automated manufacturing course.

B. Techno Da Vinci Mill by Techno, Inc. Education Division

The lab contains two Techno Da Vinci three-axis tabletop mills that were purchased in 2005 to support a mechanical systems and controls lab course. Although they were outfitted with Dremel®-style rotary cutting tools, they were used exclusively as pen plotters. The encoders were outdated technology, and the software interface was extremely challenging for the students to learn how to use. These were refurbished with all new encoders in the spring of 2012. The refurbishment took one day, and each mill cost $7500. These two mills now interface through Techno CNC Interface software directly to MasterCAM and have been the most popular ones to use in the course. They are capable of machining up to three feet square, but that requires additional fixturing. They are each outfitted with a vise that holds the wax blocks.

The Techno mills are still available for purchase and are widely supported by local distributors. They are straight forward to operate and provide a great learning environment; however, the rotary tools provide inferior cutting and the collets make tool change difficult. The collet must be removed from the rotary tool in order to put in a new tool bit. Collets of one-quarter and one-eighth inch are available, so end mill tool bits are limited to smaller sizes. Also, the gantry-style movement of the rotary bit is jerky and does not provide as nice a surface finish as the other mills we have. For safety, I had both mills outfitted with Plexiglas shields and hinged doors. I also had an air blowing system attached to each tool head to help clear wax shavings.

C. Bridgeport Explorer I CNC Mill by Bridgeport

I purchased this three-axis knee mill in 2009 off of Craigslist for $3000 and then moved it up to the university in a pickup truck using a forklift and chains to get it in and out of the truck. The mill was transported to near the door of the building and then lowered onto a rolling platform to bring into the classroom through the double doorway. It was then lifted with the forklift again and placed in its final position. It required three-phase power, which was previously installed for it during the building renovation. The Bridgeport mill was in good working condition, but very outdated. I had the computer, keyboard, and software updated for $4000. The mill was also cleaned up and painted and got a new adhesive panel backdrop for the controls. The software is a standard Fanuc controller, suitable for our machine, and I downloaded the post for it for free from MasterCAM. To place files on the machine, we purchased a special USB drive that plugs into the back. This USB drive provides access codes and also serves as extended machine memory. For safety, I had three six-foot high Plexiglas rolling walls made to surround the three sides of the machine. The machine has oil coolant, but I opted to use the mill only for wax during the course. It is capable of machining aluminum as well as steel and can support the use of large tool bits.

D. 3D Laser Scanner (Student built)

Manufacturing techniques are changing rapidly, and one trend is biomimicry and reverse engineering, where designs are organic and inspired by nature. Traditional CAD software is notoriously ill-equipped to model organic forms, so engineers are searching for new ways to input CAD geometry and surfaces into their designs. One way to input such surface data is with the use of a laser. Our device is a green line laser that is hand-swept over the object of interest. A student developed this for me in 2010. Behind the object is a grid of calibration dots that allow the software, we use David®, to capture the surface contours. The object can be rotated multiple times, and the finished scans can be aligned in the software to recreate the entire object. The surfaces are then fused together, and the finished object can be viewed in SolidWorks and printed on a 3D printer. Our 3D laser scanner is of very low quality, but it illustrates the concepts well, and students gain a lot from the awareness of such techniques.

E. Cupcake 3D Printer by MakerBot

I won this 3D printer from MakerBot in 2010 by entering an essay contest, explaining how I would use it in my courses. The printer came as a kit with hundreds upon hundreds of pieces, but if I were to have purchased it, the cost would have been only $1500. Now, they are even cheaper. Building the printer (and then optimizing it) provided several of my students with interesting focus and independent study projects that gave them valuable hands-on experience with hardware and electronics. The software is open source and is called Replicator G. The Cupcake is an ABS extruder (fused layer deposition). It works like a hot glue gun, melting the ABS plastic at 250 degrees Celsius and building layer-by-layer on the heated build platform. The build platform is less than three inches on a side, but the resolution is actually not bad for hobbyists. Like the 3D scanner, its purpose was to expose students to this new manufacturing technique, as industry is beginning to manufacture car parts and other exciting designs that could never be machined using conventional methods.

3D printing is truly the future of manufacturing. Many of our senior projects desire 3D printed prototypes, and we have had to send these requests out to local industry, as our capabilities are limited. However, a donor has given us $25,000, which we supplemented with departmental funds, and we have purchased a Stratasys Dimension 1200es SST. This new 3D printer has a 10 x 10 x 12 inch build volume and can print in nine different colors of ABS plastic. We chose this printer because it provided robust, functional parts that could be used directly as prototypes, and had relatively high resolution of .010 inches. The speed is moderate compared to other technologies, but we were pleased that the scaffolding material was environmentally safe and water soluble. Parts are placed in a water-based solvent part washer for several hours and are then rinsed in the sink. The solvent can be poured down the drain and replaced as needed. Since the water-based solvent is heated to 70 degrees Celsius, we are requiring students to wear insulated dish gloves, safety glasses, and masks, just to make sure they are not exposed to any chemicals unnecessarily.

F. Manual Machining and Vacuum Forming

In the machine shop, we have a three-axis Bridgeport mill. Students are asked to machine a paperweight out of aluminum. The purpose of this training is to help them gain a realistic sense of what feeds and speeds mean in the MasterCAM software. It also lets them feel the resistance of the machine if they make too deep of cuts or try to travel at too fast of a speed.

Also in the machine shop, we have a vacuum forming machine. The plastic material, such as polystyrene, is held in a sheet and heated from above the object to be captured. When it reaches the right temperature, the sheet is lowered quickly, and air ports in the lower table seal the plastic around the object. Finished molds are then trimmed out of the cooled sheet and can be filled with a hardening foam or plastic material to make replicates of the original object.

G. Safety

To minimize the risk to our students, we conduct two full class periods of training, one for the automated manufacturing lab and each piece of equipment it contains, and one for the machine shop. Students are not allowed into either location without safety glasses, pants, and closed toe shoes. They must use leather gloves to change tool bits and must have all shields engaged before turning on the machines. Other safety is also covered, such as tying back long hair, not wearing loose clothing, and applying appropriate force to vises and collet nuts. Both the instructor or technician and a lab assistant are present at all times. Once students are fully trained, they are permitted to use the machines outside of class time, whenever the building is open. They are required to work in pairs, and they have to carry written permission with them, in case anyone asks if they are allowed in the lab. Any injuries are reported to the university. So far, one student cut his hand on a tool bit when checking to see if the wax block was secure in the vise (it came loose). A second student used his personal pocket knife to open a cardboard box and cut his hand.

III. RESULTS

This past academic year, 25 students took this new course in advanced CAD and automated manufacturing. The students each completed over ten MasterCAM tool path codes, and about a dozen SolidWorks models. As teams of four, the students also fabricated six of their own designs, one on each piece of equipment, as well as a final project on a machine of their choice. Many students incorporated surface modeling in their designs and many others built mechanisms of several wax-cut pieces, such as the Geneva mechanism in the photo. Since then, many of these students have continued to use what they learned to make projects on their own or as part of their senior design prototypes. One team machined an entire foam RC airplane wing on one of the Techno mills for their senior project. Another used the MakeBot to make a buckle for a medical device, also for their senior project.

There have been numerous glitches throughout this first year course offering. The Bridgeport mill developed some mechanical problems and had to be repaired. It was also limited to 256 kilobyte files, and some of the feature-based milling techniques in MasterCAM exceeded this limit. I did not learn until after the semester ended that the USB drive could allow us to machine larger files. The Techno mills do not adequate grip the tool bits in the collets unless the collets are first removed from the rotary tool and assembled with the tool bit. Also, the collets were old and had some looseness. Thus, some of our early attempts failed to machine properly, because the tool bit loosened and starting falling out of the collet during machining. New collets were purchased, and the students were trained on the proper technique for changing tool bits. Hopefully, some replacement rotary tools with a chuck key system can be found in the future. The MakerBot printer was having trouble with the ABS plastic not adhering to the heated build platform. This was resolved by adding a raft under the parts. The larger, looser surface area of the raft was better at adhering. The raft then had to be peeled off the part after fabrication. Finally, the 3D laser scanner software, David® 2.0, could only produce .STL files. This is not an editable format in SolidWorks®. There are other software options out there at free or low cost, so those will be investigated.

IV. DISCUSSION

This course was very well-received by the students and received a lot of positive feedback. The overall assessment of the course by the students was 4.78 out of 5.00, with 78% giving a rating of “strongly agree” on the course being a valuable learning experience. The remaining 22% answered “agree” to this question. Below are some of the comments students made about the course:

“I really enjoyed learning the advanced CAD and automated manufacturing techniques learned during this course. I think all of these skills will be very beneficial to my career.”

“It is a fantastic introduction to Advanced CAD and Automated Manufacturing. It has been the most hands-on of any class I have had so far, and thus has been the most enjoyable. I certainly like that several different types of automated manufacturing are introduced in the lab.”

“The course teaches an engineer how to bring their designs to reality and the problems that arise in manufacturing a product from a drawing. The instructor was prepared for problems when they arose and was able to keep the course moving forward even when problems resisted.”

The students also gave me some beneficial feedback to help improve the course this next year. One of their main criticisms was the time slot. Because we needed both a computer classroom and a heavily-used lab, the course was offered at night. This interfered with student jobs, placed the course back-to-back with an optional review course many of the students were enrolled in, and limited how late we could stay, since the machine shop technician needed to go home. Thus, next year, we are switching semesters the course will be offered. In the spring semester, we can offer the course in the late afternoon with no conflicts.

Another complaint was the poor quality of the course pack I created for SolidWorks and the amount of advanced techniques we were able to cover. The students were not as skilled at SolidWorks from their introductory class as I had anticipated, so a lot of time was needed to go over more remedial skills. Most of them did not know how to create a dimensioned engineering drawing, either, so that will need to be added to the instruction next year. Because of these challenges, we did not get an in depth coverage of surface modeling. I am working with an exceptional student to develop my own advanced CAD book for SolidWorks for next year’s course.

V. CONCLUSIONS

As our knowledge of science and engineering increases in complexity, we feel it is important to maintain the hands-on skills portion of scientific inquiry, as well as to develop student ability to formulate a problem and design an engineering solution that addresses all of the many faceted issues that may be involved. As the integration of design into the engineering curriculum is now an ASME and ABET criteria, we are addressing this issue across multiple courses.

Overall, this new course offering in advanced CAD and automated manufacturing has been a successful addition to our curriculum. There is a lot of room for improvement, but the main objectives of the course, which were to give students experiential learning and thus improved design skills through hands-on manufacturing of their own designs, has been achieved. It is a future goal to assess the impact this has on our student outcomes.

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