CHAIR Award

Implementation of a Three-Semester Concurrent Engineering Design Sequence for Lower-Division Engineering Students

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ABSTRACT

Over the past decade the software products available for solid modeling, dynamic, stress, thermal, and flow analysis, and computer-aiding manufacturing (CAM) have become more powerful, affordable, and easier to use. At the same time it has become increasingly important for students to gain concurrent engineering design and systems integration experience. The purpose of this paper is to communicate the dramatic effect that the new software has had on the way that mechanical drawing and engineering design are taught at Daniel Webster College (DWC). The two year design experience at DWC is more extensive than the design experience that students normally have during the first two years of most four-year engineering programs. The evolution of this design experience will be presented. Three of the presenters of this paper are students. Two will present robotic arm projects; the third will present a supersonic gun project.

INTRODUCTION

Daniel Webster College offers B.S. degrees in a variety of majors; however, the current engineering degree programs are two-year transfer programs. The College has several articulation agreements with ABET-accredited engineering schools. Beginning in the fall of 2005 the College will begin offering B.S. degrees in both mechanical and aeronautical engineering.

Maintaining interest has been a major concern for some time in engineering education. A study done by the Higher Education Research Institute (1993)1 determined that only 51% of students who started in engineering remained in the major. The study found that the number one reason the students gave for changing their major was a loss of interest in engineering.

Elaine Seymour and Nancy M. Hewitt have written the book, Talking About Leaving (2000)2. The data they collected show that approximately 40 percent of undergraduate students leave engineering programs and that these losses occur among the most highly qualified college entrants and are disproportionately greater among women and students of color, despite a serious national effort to improve their recruitment and retention.

The CDIO Initiative3 is a partnership for bettering engineering education through multidisciplinary hands on curriculum, real world applications, and communications skills. This initiative started at M.I.T. and has gained national and international partners. The vision statement for CDIO states, "The CDIO Initiative offers an education stressing engineering fundamentals, set in the context of the Conceiving - Designing - Implementing - Operating process, which engineers use to create systems and products."

With respect to teaching and learning reform CDIO states, "We know some interesting facts about how experiences affect learning. Engineering students tend to learn by experiencing the concrete and then applying the experience it to the abstract. Unlike their counterparts of years past, many engineering students today don't arrive at college armed with hands-on experiences like tinkering with cars or building radios. Yet, hands-on experience is a vital foundation on which to base theory and science."

In the paper, Lessons Learned from Design-Build-Test-Based Project Courses (2004)4 the authors conclude, "Data describing a large number of design-build-test experiences has been compiled, enabling comparisons and constituting an idea catalogue. The data indicates that these experiences do indeed motivate students, integrate different engineering disciplines, train system development and non-technical skills such as teamwork and communication, and thus play a key part in engineering education. These educational experiences further receive very positive evaluations from students, faculty and industry stakeholders."

The opportunity for engineering students to have early and frequent hands-on design experiences is critical both for learning and retention. This paper describes the evolution of the design experience at DWC.

At DWC the three-semester concurrent engineering design sequence has replaced the more traditional courses of Engineering Graphics, C Programming, and Probability and Statistics, and/or Chemistry II. Visual C++ and some probability are integrated into the new design sequence. The new sequence emphasizes the use of hands-on design projects and gives students concurrent design experience. In concurrent engineering design, all phases of product development are considered simultaneously. A common database is used for geometric modeling, engineering analysis, animation, computer controlled manufacturing, and product documentation.

Professors Barr, Krueger, and Aanstoos aptly describe this process in their paper, The New Digital Engineering Design and Graphics Process (2002)5. In their paper they also provide an engineering design graphics curriculum outline based on the digital design process. It consists of eight laboratory modules and a two-week design project.

We felt that this concurrent design experience was so important to our students' engineering education that in 1998 we expanded our existing engineering graphics course to a three-semester concurrent engineering design sequence.

In their project work the students must make appropriate simplifying assumptions and do a manual analysis of their systems to determine things like maximum stresses and deflections, accelerations, and the required time for certain movements. They then perform the same analysis on the solid models of their systems using the simulation software. Next, they use CAM software to generate G and M code in order to machine their parts. Finally, they assemble and test their systems and compare the experimental results to the manual and computer simulation results.

By going through this three-step process of analysis, the students increase their confidence and ability to analyze complex systems. Advances in the software have made it possible for students to quickly learn how to produce quality models and drawings, including animated assembly drawings.

We have found that this approach to design has increased student interest, understanding, and motivation. Our retention rate has gone from around 50% to over 80% and approximately 30% of our students are women.

GRAPHICS (AT DWC) PAST, PRESENT, & FUTURE

The theme of this year's EDGD annual midyear meeting was Graphics – Past, Present, & Future? In this section we will recount the evolution of the engineering design graphics experience at DWC as well as convey our plans for the future.

- 1986 - DWC obtains AutoCAD R2.1 which is run on Rainbows with 256 K RAM (wow!) and requires swapping 5.25" floppies for some commands. Awkward, but a huge step forward from drawing on the board. Layers are wonderful, as is perfect lettering every time. Eight years of new releases with improved functionality and increased computer power follow and mechanical drawing on the board is gradually phased out.

- In December of 1994 DWC starts a FIRST robotics team with Alvirne High School in Hudson, NH. During the first six months of our involvement with the team, we managed the team and coordinated the design, but we had no college student involvement from DWC. We asked Lockheed Martin Commercial Electronics, a local company, to help us. They supplied approximately eight engineers and machine shop help. They did all the fabrication at their facility.

- 1995 - DWC obtains AutoCAD R12 with AME which is run on computers with 4 M RAM. Again, awkward, but neat. This year we had two students from DWC get involved with the FIRST team, but none of the fabrication was done at DWC. Our shop facility consisted of a work bench with a drill and a few hand tools. Our two-year curriculum at that time had no design courses and one engineering graphics course, which was essentially a 2-D mechanical drawing class using AutoCAD. In most engineering programs at that time, design was not taught until the junior or senior year. It has been said that if traditional engineering education programs taught baseball, they would not even let the students touch the ball until they were seniors. Through our experience with FIRST we were beginning to see the power of open-ended design experiences to teach and motivate students.

- In August of 1996 one of our faculty members attended an NSF Concurrent Engineering Design Workshop at the University of Texas at Austin led by Ronald Barr and Davor Juricic. This workshop demonstrated the power and potential of the concurrent engineering paradigm and reinforced our impressions from the FIRST experience that giving students design experiences early and often needed to be a priority. Some of our sophomore engineering courses required design projects, but due to the large amounts of theoretical material required in these courses, we found there just wasn't time for the kinds of significant design experiences we wanted our students to have.

- In June of 1997 a faculty member attended an NSF CAD/CAM Integration workshop held at Cincinnati State Technical and Community College led by Brad Harriger, Daniel Newby, and Larry Reuss. After attending the workshop, participants prepared CAD/CAM Integration modules for submission to the Midwest Center for Advanced Technological Education (MCATE). Participants presented their modules in October of 1997 at Purdue. After participating in this workshop we were more convinced than ever that we needed to give our students a concurrent engineering experience, and we began to acquire the various software tools necessary for this work and to outfit a machine shop to support it. In December 1997 we obtained an examination copy of Pro-Engineer and hoped to use it that spring for the FIRST robot design. We found that the learning curve for this software was too long, so we continued with AutoCAD AME. This is not to speak badly of Pro-Engineer. It is a very powerful software package, but for our purposes it was too time-consuming to learn. PTC now has a product called Pro/ENGINEER Wildfire that compares favorably with Inventor, SolidWorks, and Solid Edge in terms of ease of use and cost.

- September 1998 – DWC introduces a three-semester design sequence. We felt that we needed a drastic change, so for all the reasons listed above we introduced a three-semester sequence of design courses.

- January 1999 - DWC obtains MDT3.0 one week before the FIRST competition comes out. Our students, who had learned AutoCAD the previous semester, were able to learn Mechanical Desktop well enough in one week to be able to use it to design the FIRST robot in less than three weeks.
- September 2001 – DWC begins using adaptive modeler Inventor which is even easier to learn than MDT.
- December 2002 – DWC obtains a Makino CNC 3-axis Milling Machine with a 28"x14"x14" XYZ machining envelope (see Figure 1), which along with Mastercam and Surfcam provide CAD/CAM capability on campus. Students begin their engineering graphics work directly with solid modeling and AutoCAD is dropped completely from curriculum.
- January 2003 – DWC obtains Visual Nastran 4D which can do dynamic and stress analysis simultaneously and maintain an associative link with Inventor. A lathe is obtained in September 2003 and the complete on-campus concurrent engineering design experience at DWC becomes a reality.
- September 2004 – DWC obtains a 30,000 RPM spindle to make possible the machining of very small parts and complicated surfaces.

With regard to the future, we believe that standardization and modularity in design will become more important as well as system integration skills. An increasing number of useful pre-engineered components for mechanical systems are commercially available. In addition, an increasing number of solid models for these components are now available on the Internet. Engineering students should be knowledgeable about what components are available and how to utilize them in their designs, as well as how to insert their solid models into system assemblies. The design sequence should provide students with systems integration experience, which also incorporates things such as vision systems, sensors, controls, and the software that ties them together.

DWC plans to begin offering B.S. degrees in aeronautical engineering and mechanical engineering next year. The proposed DWC engineering programs both contain six-semester concurrent engineering design sequences that will steadily build the experience needed for successfully dealing with the many issues facing the engineer of the future.

Figure 1: *CNC Makino 3-axis Milling Machine*

THE THREE-SEMESTER DESIGN SEQUENCE

The course numbers for this sequence are EG110, EG112, and EG205(Recently changed to EG310). Syllabi for these courses can found at the following link:

http://faculty.dwc.edu/bertozzi/

In the first course, students are introduced to the Identify-Ideate-Refine-Analyze-Decide-Implement engineering design process. Students learn how to create solid models and generate the various standard views as well as animated assembly files, and surface area, volume and mass properties.

They are also introduced to a number of software tools for use with arrays and matrix algebra, statistics, word processing, and spreadsheets, and the use of the Internet for research and the electronic transfer of design data. Using both Excel and Maple, students learn how to generate a gear tooth involute curve based on pressure angle, diametral pitch, pitch diameter, addendum, and dedendum. A basic introduction to statics, strength of materials, and dynamics is provided.

Projects for this first course typically require an understanding of torque and power curves and gear reductions. Design projects are undertaken by groups of two to four students. Groups are required to give class presentations and submit project proposals, weekly progress reports, and a final technical report.

One of the outcomes for this course is that students will be introduced to a variety of shop equipment including lathes and millings machines, and utilize this equipment in the construction of their working prototypes. Our experience has been that some students come to DWC with good machine shop experience, while others have no experience working with tools and machinery. Our goal is that all students advance to the same level by the end of the first semester.

To facilitate the learning experience in the machine shop, we have trained sophomore students to teach the freshmen proper machine shop practices and to oversee the use of the equipment when the freshmen design teams build their prototypes. This has been a very positive experience for both the freshmen and the sophomores. It is also a cost-effective way of doing training for the College.

We mentioned earlier in this paper that approximately 30% of our students are women. As freshmen we offer the female students the opportunity to be trained in the use of shop equipment by a female sophomore student. Most prefer this option. Most of our female students come in with no hands-on experience using tools of any kind. However, our experience is that by the end of the freshman year, as a group they are just as capable in the shop as the male students, a fact of which they are quite proud.

The second design course is taken during the spring semester of the freshman year. In the first third of this course students continue to gain experience in the use of solid modeling tools. They do more advanced assembly modeling exercises and learn how to control both parts and assemblies with an Excel spreadsheet. One of the assignments for this course is to connect involute curve data generated from an Excel file to a solid model and create a gear. With this model they can then machine any size gear they need for their projects. Creating the gear profiles in this way, rather than using a canned package to generate the profile, helps them to better retain an understanding of the important gear parameters.

In the final two thirds of this course students are expected to analyze engineering problems and write, test and debug C++ solutions to those problems. They continue working on their design projects throughout the semester.

The third design course is taken in the spring semester of the sophomore year. Students continue to build on their design experience from the previous two courses. Working directly from their solid model data bases they perform finite element analysis (to determine stresses and deformations), motion and dynamic analysis, manufacturing simulation, CNC code generation, assembly modeling and tolerance checking, as well as drafting and documentation.

EXAMPLES OF STUDENT PROJECTS

In this section we will discuss some of the problems and projects that students have worked on in the design sequence.

As was mentioned earlier, DWC sponsors Alvirne High School in the annual FIRST robotics competition. In this program companies and colleges help high school students build robots for regional and national competitions in an effort to help them realize how exciting careers in science, engineering, and technology can be.

The competition rules are generally unveiled on the first Saturday in January, after which time teams have six weeks to strategize, and design, manufacture, assemble, and test their robots. Since Engineering Design II and III are spring semester courses, DWC students have the option to return from winter break early and work on the FIRST robot as their design project.

In the spring of 2004, five freshman and three sophomores led the design teams for the eight mechanical systems on the robot. A fourth sophomore wrote the software for a drift correction system that could be used when the robot was operating in autonomous mode. The DWC students had to work with the high school students as well as coordinate their designs with each other. A picture of the robot is shown in Figure 2. Before the parts for the robot were manufactured, a complete solid model was created by the students. This is shown in Figure 3. The robot performed very well in the competitions. A picture of the robot at the nationals in Atlanta is shown in Figure 4.

Figure 2: *2004 FIRST Robot*

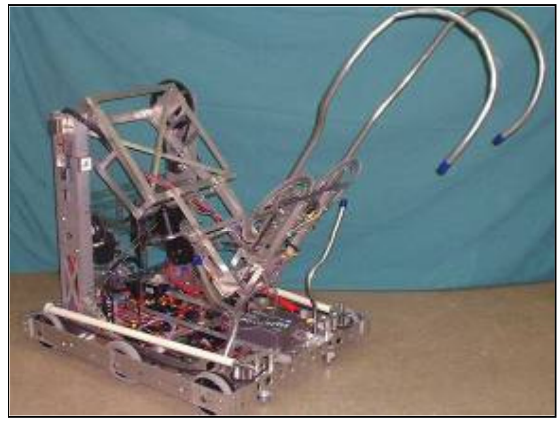


Figure 3: *FIRST Robot Solid Model*

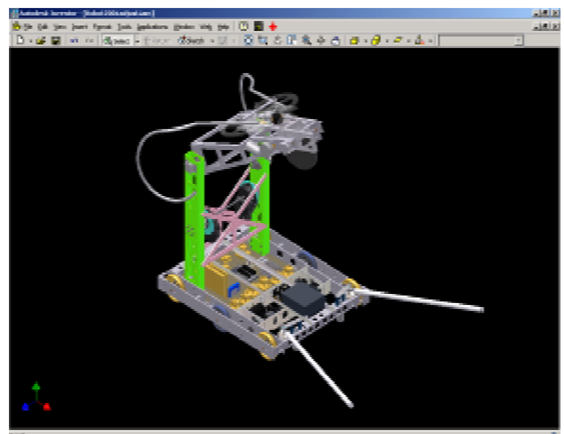


Figure 4: *FIRST Robot at Nationals*

Figure 5: *Lexan Docking Assembly*

Figure 6: *Lexan Pinion on Ford Window Motor*

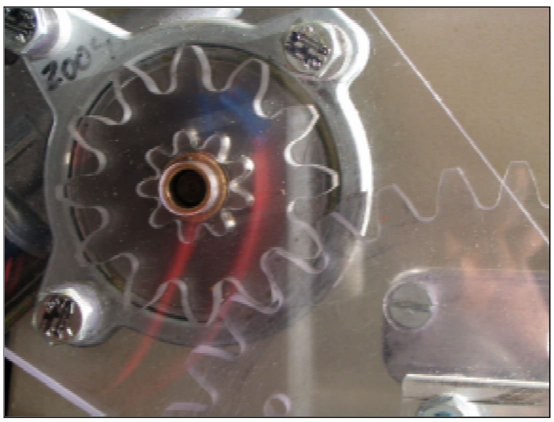


Figure 7: *Grabber Assembly Drawing*

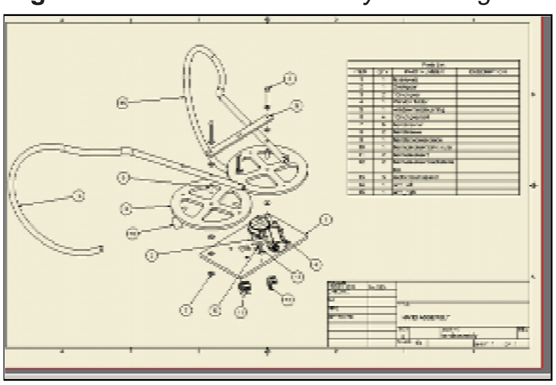
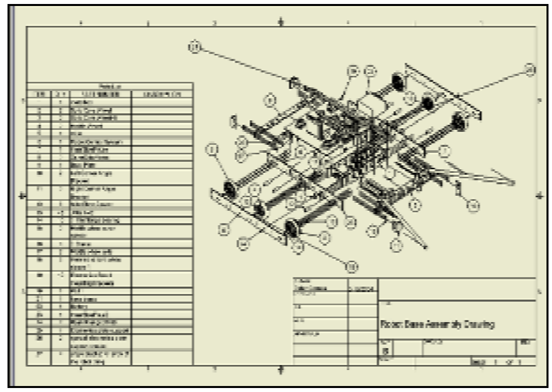


Figure 8: *Robot Base Assembly Drawing*



A picture of a goal docking mechanism is shown in Figure 5. The supporting fixture, pinion, and docking arm are all made out of Lexan. A gear tooth profile has been integrated into the docking arm. An interior gear profile, as well as an exterior profile was machined on the pinion, which is driven by a Ford power window motor (Figure 6). This was done so that a pinion with the desired pitch diameter could be placed right on the power window motor. We have found Lexan to be a delightful material to work with. It machines beautifully without any coolant, and is tough and light. This docking arm took a tremendous beating, yet did not break.

Figures 7 and 8 are assembly drawings that were done by students in the second design course. With the solid modeling software, these drawings were easy to create and contain BOM's that were generated automatically. The BOM's can also be exported to an Excel file. The students create animated assembly files as well, which can be played with Window Media Player.

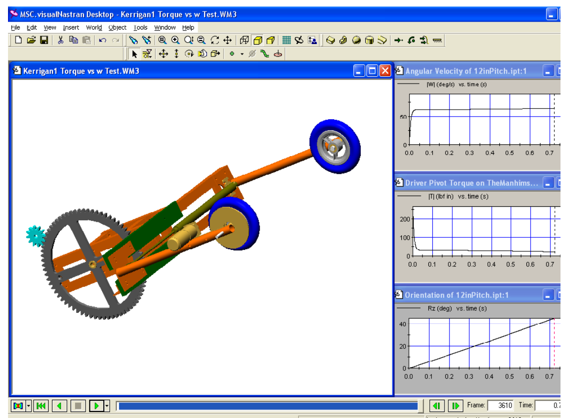
As was mentioned above, students gain an understanding of torque and power curves, and gear reductions, while taking the first design course. They built a four-motor, six-wheel-drive system for the 2004 FIRST robot. This system required running two different motors in tandem on each side of the robot.

The students had to determine the best ratio for coupling the motors in order to get the maximum possible power output, as well as determine the best second stage ratio out to the drive wheels to optimally meet design requirements. A picture of the drive system is shown in Figure 9.

Figure 9: *Robot Drive System*

In the third design course, students learn how to use Visual Nastran 4D, which can do dynamic analysis and stress analysis on their assemblies simultaneously. An example of this is shown in Figure 10. This is a forearm and grabber mechanism that was built for the 2003 FIRST competition. It was able to pick up crates and rotate them to the correct orientation so that they could be stacked on other crates.

Figure 10: *Visual Nastran 4D Simulation of Arm with Variable Torque Motor Driving*



A virtual motor has been attached to the pinion in Figure 10. The 12 volt dc motor used on the robot has a torque versus angular speed curve that can be modeled with a formula and attached to the virtual motor. Typically of dc motors, as the speed increases, the available torque decreases. Conversely, as the torque requirement increases, the speed decreases. You may have experienced this relationship first hand (pardon the pun) while using a cordless drill. Once this formula is attached to the virtual motor, the robot arm model will perform in the same way as the actual arm.

Figure 10 shows the arm after the motor has been turned on at full power until the arm reaches a position of 45 degrees from the horizontal. It can be seen in the top graph on the right that the angular speed of the arm is 64.4 degrees/second and the time required for this movement is 0.722 seconds.

It can also be seen in the middle graph on the right that as the angular speed increased, the available torque decreased as expected.

A stress analysis test was also done on the pinion in order to verify that the face width was large enough to avoid failure. This is shown in Figure 11.

Figure 11: *Stress Analysis Test to Verify Sufficient Face Width on Pinion*

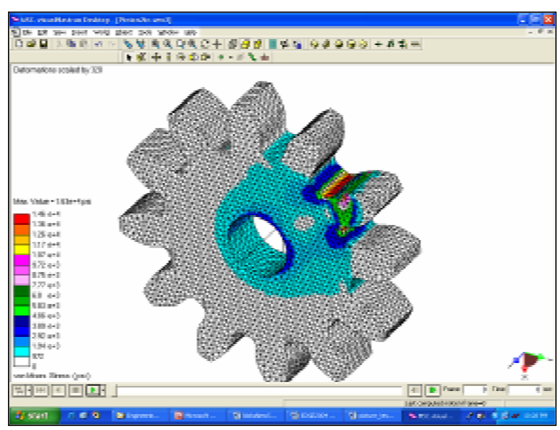


Figure 12: *CNC Makino machining large elbow gear*

Figure 13: *Radial Deflection Analysis*

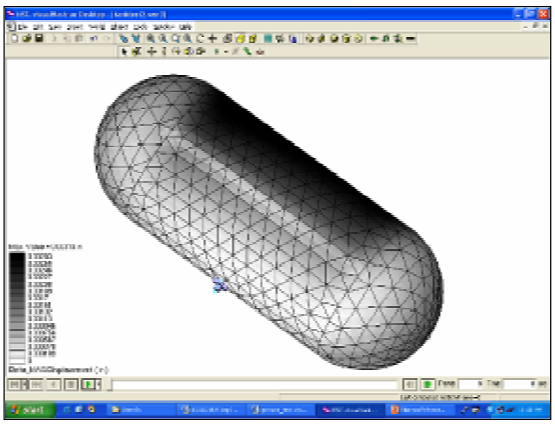


Figure 14: *Longitudinal Deflection Analysis*

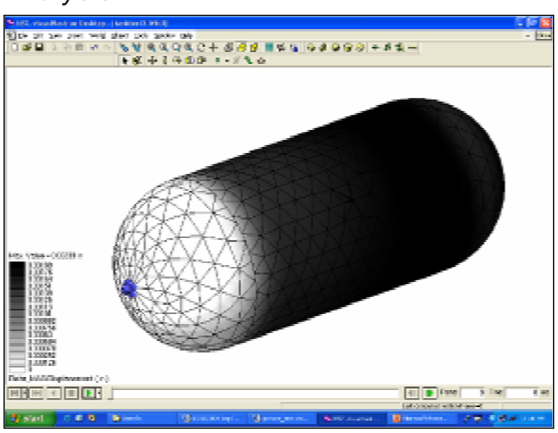


Figure 12 shows the large elbow gear for this assembly being machined on the CNC Makino.

When students first start learning how to use Visual Nastran 4D they do some problems that can be easily solved manually and/or easily tested experimentally.

For instance, it is easy to solve the deformation of a cantilever beam manually and to measure the deflection in the lab, and compare these results to the simulation result.

When a team of students wanted to design a supersonic gun for their Engineering Design III course they needed a very high pressure reservoir. Because they had never tried to model pressure inside a tank before with Visual Nastran, they first simulated a cylindrical tank with hemispherical ends. It is easy to calculate the longitudinal and hoop stresses for this type of tank, as well as the deflections. These results could then be compared to the simulation results, and the procedure allowed the students to gain some confidence.

Such a tank is shown in Figures 13 and 14. In Figure 13 the tank is fixed on the side, so that the maximum radial deflection can be determined. In Figure 14 the tank is held from the end, so that the maximum longitudinal deflection can be determined. The results agreed well with the manually calculated results.

The solid model of the supersonic gun assembly can be seen in Figure 15. In the section view shown in Figure 16 the converging-diverging nozzle that the students designed can be seen.

The students needed to preload the support tripod for the assembly before the chamber could be pressurized. The simulation for the deflection caused by this preloading is shown in Figure 17. The students also calculated this deflection manually, after making some simplifying assumptions. Once the parts were made, they measured the deflection in the lab. They were able to get good agreement between the three different methods of determining the deflection.

One of the benefits of the three-semester design sequence is that the students can use their design, simulation, and manufacturing skills for projects in their other engineering courses.

In the aerodynamics course, which is taken in the second semester of the sophomore year, the students do wind tunnel testing with a wing that has a rectangular planform, 10 inch span, 2.5 inch chord, and a NACA 0015 airfoil section.

The students have to make a linearly tapered wing and an elliptical wing that have the same airfoil section, span, planform area, and aspect ratio as the rectangular planform wing. The tapered wing must be designed with a taper ratio that will produce the minimum possible induced drag for a tapered wing. Theoretically, the elliptical planform wing should have the minimum induced drag of any planform shape. Once the wings are made they can be tested in the wind tunnel and their lift coefficient and drag coefficient curves compared to the theoretical predictions.

To create the solid model of the elliptical wing, an Excel file containing the NACA 0015 airfoil data is imported into an Inventor part file and onto a sketch of the elliptical planform. This is shown in Figure 18. A loft can now be created and mirrored to create the wing, as shown in Figure 19.

CAD/CAM software can now be used to create the tool paths needed to make the part. One of the great things about the CAD/CAM software is the virtual machining feature. This allows you to see what is going to happen when the G and M code is run. It greatly reduces the anxiety of the instructor when students without a lot of experience are learning how to run CNC equipment. Virtual machining of the elliptical wing is shown in Figure 20.

Figure 15: *Inventor Solid Model of Supersonic Gun*

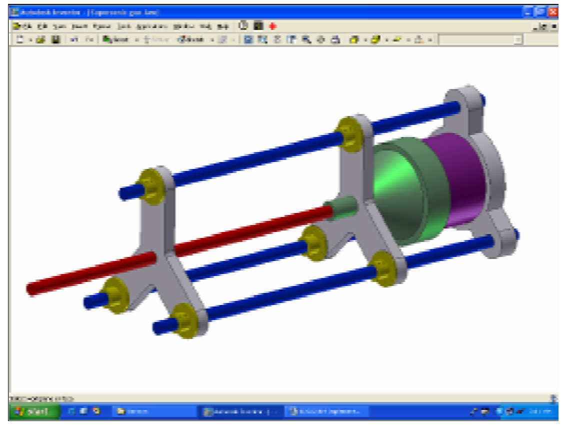


Figure 16: *Section View of Converging-Diverging Nozzle for Supersonic Gun*

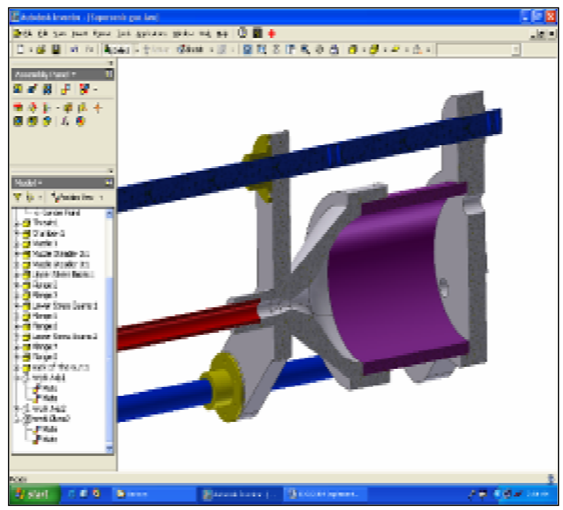


Figure 17: *Deflection Analysis of Support Tripod*

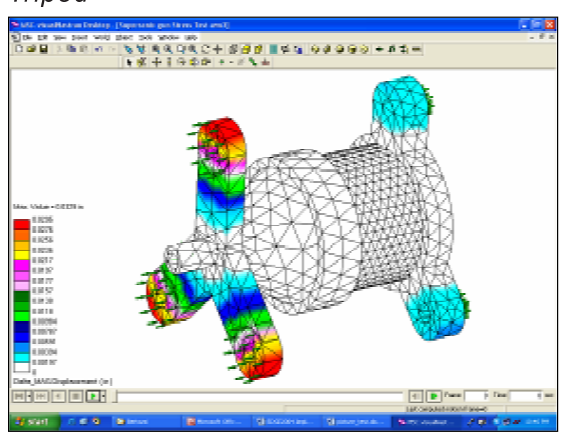


Figure 18: *NACA 0015 Airfoil Data Imported into Inventor Part file and onto Elliptical Planform*

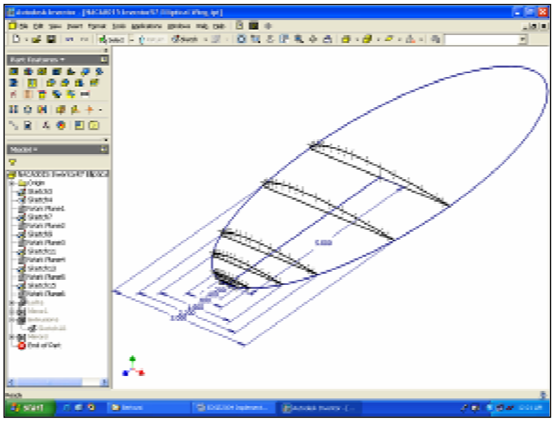


Figure 19: *Loft through Section Sketches*

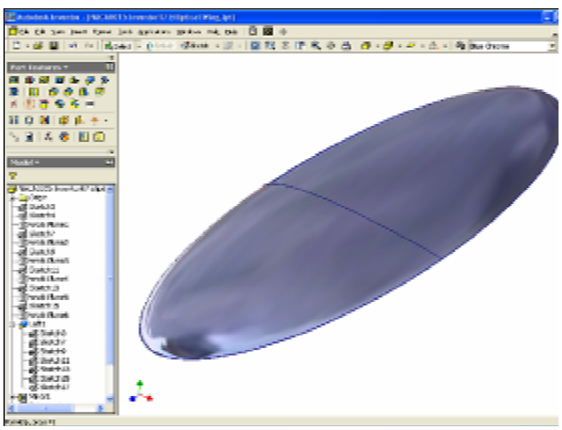


Figure 20: *Predator Virtual CNC Machining of Elliptical Wing*

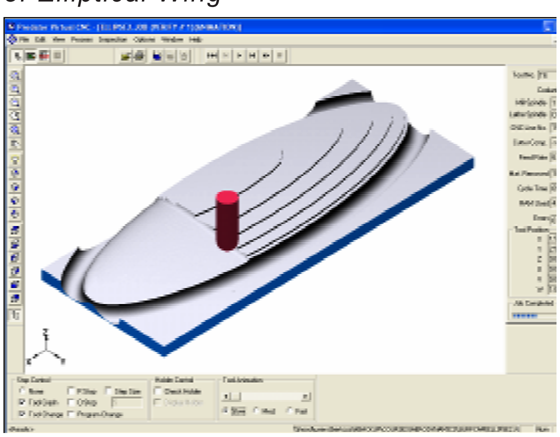


Figure 21: *Three wings and aluminum negative*

The wings shown in Figure 21 were made out of blocks of Lexan. Machining the top surface is straight- forward. To machine the bottom surface is more difficult because there are no flat surfaces to hold on to. To solve this problem the students first machine a negative (which is shown in the upper left corner of Figure 21) and put in some tapped holes for tie down screws. Two holes are reamed for dowel pin insertion in order to provide for very accurate positioning. The students have been very happy with the quality of the wing models that they have been able to produce.

CONCLUSIONS

From the mid-eighties through the mid-nineties, 2D CAD software began to make mechanical drawing much easier and gradually replaced the drawing board. However, it did not significantly change the way engineers did mechanical design.

During the past decade the software and hardware available for solid modeling, analysis, simulation, and CAM have become more powerful, affordable, and easier to use. These products have significantly changed the way we do mechanical drawing and mechanical design. They have also taken a lot of the tedium out of mechanical design, thereby making it more fun.

Parts and assemblies can be easily modified and drawings updated all while maintaining an associative link with analysis software, so that many "what-if" scenarios can be considered. This is not to imply that there is any less need for engineers to understand the theoretical concepts associated with design. Indeed, this understanding is essential for identifying critical areas of analysis, and for getting the full potential out of the software and correctly interpreting the results it provides.

At DWC, students use a three-step process of analysis. First, the students must make appropriate simplifying assumptions and do a manual analysis of their systems. They then perform the same analysis on the solid models of their systems using the simulation software. Finally they manufacture, assemble, and test their systems and compare the experimental results to the manual and computer simulation results.

Another benefit that results from this process of having students manufacture their own parts is that they are more motivated to find the simplest solutions to their design problems. When we didn't have the manufacturing equipment on campus and sent designs out to be made, the students tended to create more elaborate designs that didn't necessarily function any better than simpler solutions.

We have found that early and frequent exposure to concurrent engineering design has increased student interest, understanding, and motivation in their more traditional, theoretical engineering courses, as well as in the engineering field in general. Retention has improved, and our engineering students have become our best recruiters of new students. Some of our other engineering courses still require design projects; however, our concurrent design sequence allows our students to focus a more significant amount of time on a design project of their choosing.

The multiple design experiences also increase student confidence and competence to tackle design problems. Concurrent engineering and systems integration skills have become increasingly important to employers as well.

Our experience with engineering students at DWC is that they long to be creative. They enjoy their more traditional engineering courses, but we see the biggest smiles (Figure 22) when they are in the shop seeing their designs come to life. There is great satisfaction in designing a system, making and assembling the parts, and having everything fit together and work the way it is supposed to.

At DWC, we believe that the positive benefits of concurrent engineering design experiences warrant additional dedicated courses beyond a freshman graphics course.

On a final note, we would like to encourage other faculty, especially those at small colleges who may not currently have all the software or equipment needed for a concurrent engineering design program, to consider moving in this direction. This has been a long journey for us, where little by little we have been able to increase our capacity to do this type of work on campus and to handle increasingly difficult projects. When we started, we had no one with CAM or even manual machine shop experience. However, we found local industry to be very helpful and their machinists more than willing to answer our questions and give us advice. As our journey continues we are very enthusiastic about what lies ahead.

Figure 22: *Everything fits and it works!*

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BIOGRAPHICAL INFORMATION

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