Computer-Aided Design and Applications

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Product Centric CAD Education

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ABSTRACT

Mechanical engineering graduates are expected to possess a working knowledge of modern Computer Aided Design/Computer Aided Manufacturing/Computer Aided Engineering (CAD/CAM/CAE) tools. The instructional challenge is to balance fundamentals with applications, and theory with practice. Many courses teach CAD from a mathematical base. This approach emphasizes "what do you know" evaluation without addressing "what can you do" expectations of both students and employers. This paper approaches instruction from a product centric perspective that, with each step, progressively builds skills and knowledge from mechanical dissection and solid modeling fundamentals towards original product design, prototyping, and testing. In first year, student teams dissect a product and produce solid model parts and assemblies. The upper year courses require product design to the prototype stage, with consideration of optimization and manufacturing issues. Incorporated subject material includes organizational behavior and team building, solid modeling theory, finite element analysis, CNC machining, rapid prototyping, and moldable part design. Implementation experiences in actual courses are described and discussed. Suggestions are provided for others contemplating similar initiatives.

Keywords: product development, mechanical dissection, design for manufacturing, team building.
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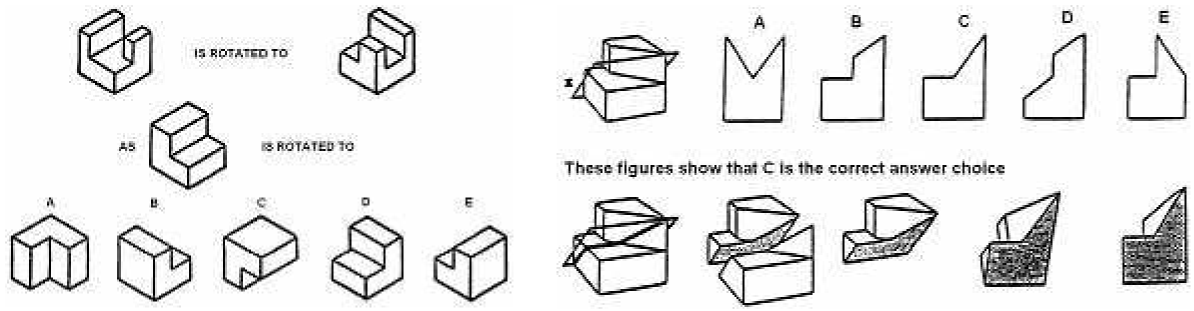
1. INTRODUCTION

Students enter engineering with an enthusiasm to create. This may have come from high school experiences, summer camps, or media exposure. University level engineering education, however, very quickly gets down to, subject by subject, teaching analysis. Mechanical engineering students take separate courses on numerical methods, mechanics of materials, mechanical elements, and CAD/CAM/CAE. The subjects are taught by different instructors, without a common thread. Knowledge is tested by examinations, but practical ability is insufficiently assessed. When new subjects emerge, the usual approach is to hire a new instructor, and, without any integration, add a new course. There is a reluctance to drop any material, and so students end up frustrated with mushrooming degree requirements that, for many, require more than four years to successfully complete [1].

Subject based curriculums are convenient, in that each course can quantitatively be assessed through conventional tests and examinations. A criticism of the subject based learning approach is that many examples are contrived and not based on any actual situation. Students then begin to see their education as removed from the real world, become discouraged, and consider dropping out or changing faculties, particularly after low grades are received. The subject based engineering "just in case" instruction contrasts with the "just in time" and case study based learning methods that are being adopted in business, law, and medical school education [2]. The isolated courses lack a real world design workflow framework and hence, when unstructured problems later arise, students have difficultly moving beyond recital of textbook examples. In professional practice, this inability creates difficulties in translating research and development invention into profitable innovation [3] and national economic activity.



(a) (b)

Fig. 1: Contrived spatial visualization test parts: (a) PSVT-R [5]; (b) MCT [6].

A significant effort to introduce workflow into the engineering curriculum is the Conceive-Design-Implement-Operate (CDIO™) syllabus [4]. This initiative recognizes the tension between an ever increasing body of technical knowledge, and the need to actually function in engineering practice. It emphasizes the need for graduating engineers to be competent in the engineering process, including product development within organizational teams. Because modern product design depends on software, CAD/CAM/CAE offers a significant opportunity to implement many CDIO™ goals.

This paper describes initial experiences in developing and delivering a new product centric, CAD/CAM/CAE based curriculum. The courses were offered to first year engineering undergraduate students, as well as second and upper year mechanical engineering students. Remaining sections are organized as follows. Section 2 describes the prior state, including the desired subject coverage. Section 3 explains personal development that is necessary to prepare participants to embrace the new curriculum. A description of the new implementation, including illustrative examples and discussion, is presented in Section 4. Conclusions appear in Section 5.

2. PRIOR SUBJECT COVERAGE

2.1 First and Second Year

The prior course and subject arrangement is typical for engineering departments. Students take a faculty wide common first year, including a course in engineering graphics/solid modeling. They then enter specific departments (electrical, mechanical, civil, software, etc.) in year two. In the second year of mechanical engineering, courses include mechanics of materials, mechanical design elements, and a group design project.

The first year graphics/solid modeling course includes spatial visualization skills testing, using the Purdue Spatial Visualization Test – Visualization by Rotations (PSVT-R) [5] and Mental Cutting Test (MCT) [6] (Fig. 1). Although, in general, student performance on these tests increased [7], the examples are contrived, leaving students disillusioned.

In second year, a variety of student group projects have been tried over the years. Projects prone to failure are those that are either too complex, or require knowledge that exceeds student preparation. A particular problem is that, due to a variety of program choices, some students do not complete the second year design project until third year. They are often intolerant of their less prepared second year peers, and resist including them when marks are at stake.

2.2 Upper Years

The upper year curriculum included separate courses in numerical methods, mechanical element design, Computer Aided Design, Computer Aided Manufacturing, and Finite Element Analysis (FEA). There was little integration between these subject based courses, but some wasteful overlap. For example, the numerical methods course included splines, and the CAD course included B-splines. In general, mechanical engineering students dislike mathematics without application, and were disillusioned by emphasis on solid model boundary representation topology, properties of B-spline basis functions, CNC G-codes, etc. Assignment copying was frequent, requiring either a blind eye or aggressive policing. Ability to apply concepts to actual product development problems, as observed by performance in the upper year capstone design project course, was disappointing.

3. STUDENT/FACULTY PERSONAL DEVELOPMENT

To achieve successful implementation, the natural resistance to any new curriculum must be overcome so that the changes are accepted by both the students and the faculty. Resistance is frequently based on fear and lack of trust. To overcome this, assessment and training in Emotional Intelligence (EI) [9] and team building [10,11] is being

Tab. 1: McMaster faculty of engineering employer intention survey (condensed from [8])

Types of Engineers Planning to Hire	
Mechanical	59.5 %
Electrical	46.3 %
Software	27.3 %
Computer	26.4 %
Chemical	24.8 %
Civil	17.4 %
Materials and Metallurgical	15.7 %
Environmental	11.6 %
Engineering Physics	8.3 %
Other	8.3 %
Biomedical Engineering	3.3 %

Development that will have the Most Impact on their Organization	
Engineering Design	64 %
Software Developments	46 %
Environmental Regulations	36 %
Technology Transfer	28 %
Commercialization	17 %
Computational Engineering	17 %
Public Policy	12 %
Mechatronics	11 %
Biomedical Engineering	8 %
Nanotechnology	6 %

Factors Influencing Choice of Universities from Which to Recruit	
Well-Roundedness of the Graduate	64.4%
Good Hiring Track Record	57.8%
Reputation	54.1%
Specialty Programs	40.7%
Strong Corporate Ties with University	21.5%
Large Recruiting Pool	18.5%
Other	13.3%

Skills and Qualities Organizations Look for When Hiring a Graduate	
Related Work Experience (Internships, Co-op)	99%
Soft Skills (Leadership, Teamwork, Collaboration)	94%
Specialized Knowledge	93%
High Marks	84%
Post-Graduate Education	74%

introduced. Faculty, teaching assistants, and staff often express concern about student classroom behavior, poor attendance, and aggressive encounters when discussing grades, access to machine shop facilities, etc. The need for soft skills is increasing recognized by society and, for engineering graduates, was specifically emphasized in a recent university administered employer survey (Tab. 1). It is a required item for Engineers Canada [12] and ABET [13] accreditation.

Particular issues in the training include recognition of fundamental attribution error – our natural tendency to excessively blame character for the faults of others, rather than look for situational explanations. This leading conflict initiator offers explanation for why students blame instructors or other team members as the cause of their own circumstances. Solution includes changing from the blaming style of "you" statements" to the ownership style of "I" statements. Some university environment observations are listed in Tab. 2. The idea is to reinforce the EI "know yourself first" principle so that everyone in the community takes a "6 second pause" [14] or uses the "gap between stimulus and response" [15] to wisely assess their own emotional state when offended by the actions of others. This habit must be practiced so that it becomes automatic even during times of high stress or cognitive overload. Unless a real crime has been committed, continuing acceptance requires that the community offer grace when anyone falls short.

4. UPDATED CURRICULUM

4.1 First Year Engineering

In first year engineering the challenge is to provide and reinforce a fundamental knowledge basis [16], particularly with the common first year program offered at McMaster. This must be balanced with a structured procedure for demonstrating capability to apply the knowledge. Additionally, students must be instilled with an enjoyment and motivation for learning, and a genuine intellectual curiosity about engineering in the world that surrounds them. To accomplish this, mechanical dissection was introduced into the curriculum.

4.1.1 Initial Summer Offering

The dissection method of teaching design has been applied to first year engineering courses [17-19] as an effective learning method. At McMaster, this approach was initially introduced in a summer 2007 course with an enrollment of 41 students. These are students that typically struggled with the course material in the previous year. At the conclusion of the summer course, the project was very well received by the students. The best illustration of this enthusiasm was the student response that "I actually felt like I was an engineer."

4.1.2 First Regular Term Offering

Based on the success of the summer course, the mechanical dissection project was next included in the September - December 2007 regular term course offering, with an enrollment of 420 students. The course consisted of a weekly lecture, hands-on CAD laboratories, and freehand sketching tutorials. The three components run in parallel. Lectures introduce new topics, labs develop CAD and solid modeling skills, and tutorials teach freehand sketching and visualization skills. It was observed that students had difficulty connecting the each component, and it was intended that mechanical dissection would provide the missing cohesion.

For the dissection project, student groups were restricted to three members within the same tutorial section. Each group is to imagine that they are newly hired engineers assigned to evaluate a competitor's product. The group must conceptualize how the device works, benchmark the product, and create a technical report with complete engineering drawings. Products are selected based on number of parts (30-60), safety, cost (<$15), and availability. For the September 2007 course, the products were a mechanical ball mouse, wind-up LED lantern, disposable camera, random orbit polisher, and a odometer style counter. Project activity is divided into two components: conceptual and applied.

4.1.2.1 Conceptual Component

With only a visual inspection of the exterior of the product, the team must sketch several isometric pictorials and explain how the product works in a short report that references additional hand sketches of the internal operation. They must also state the total number of parts that make up the product and propose a benchmark procedure. This component has two goals: i) independent research; and ii) technical communication.

4.1.2.2 Applied Component

In the applied component portion of the project the group must: i) benchmark the product and record results; ii) disassemble the product; iii) measure and model each part using a solid modeling software application; iv) assemble the product in the software application; v) re-assemble the physical product; vi) benchmark the product and record results; and vii) write a technical report of how the product works with a compete set of engineering drawings.

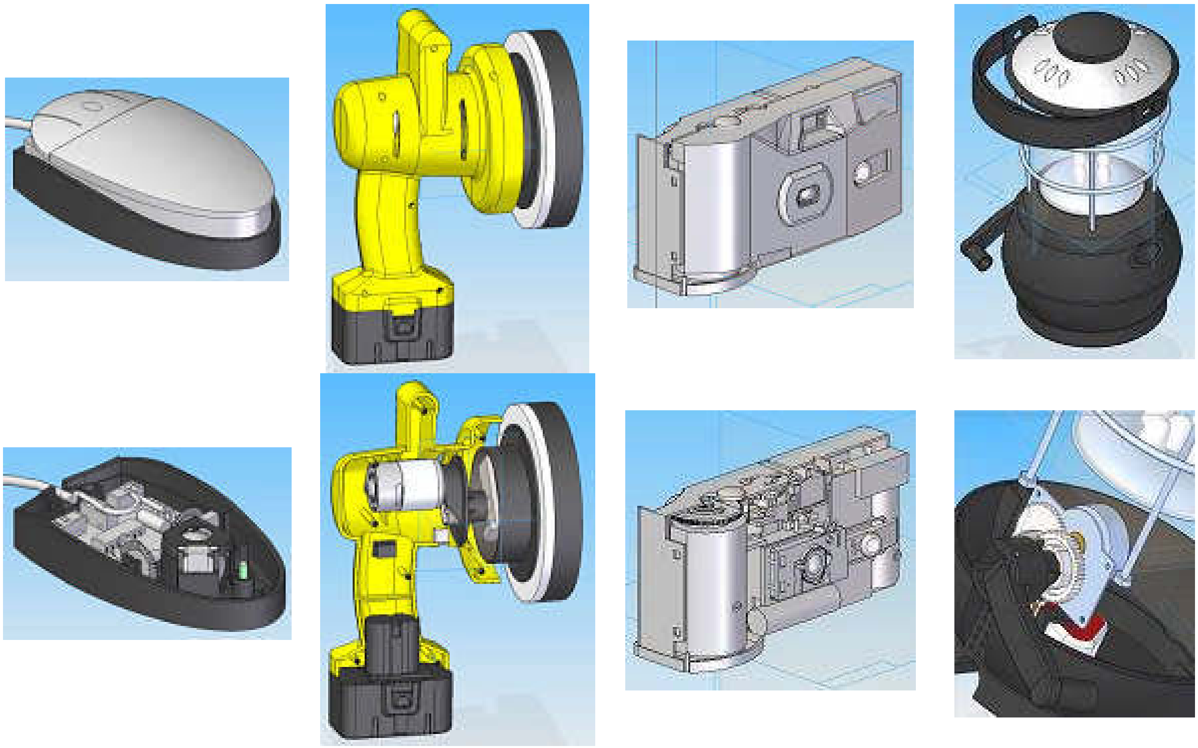
The group members distribute the parts evenly among themselves for modeling and then recombine them for reassembly. A level of approximation is permitted according to the part complexity and mechanical function. For example, a part which is key to the mechanical function of the product would be permitted very little approximation. Assembly requires integration of parts from different group members, with team modifications to minimize interference. Submitted material consists of a final report including a technical description of product operation, benchmark results, bill of materials, a part characteristics table (surface area, volume, radii of gyration), and a complete set of engineering drawings. An oral examination is scheduled to evaluate, both as a group and individually, knowledge and contribution to the project and related course components. Fig. 2 illustrates the quality of final submissions and the complexity of the products.

4.1.3 Discussion

The products chosen are commonly available, and are expected to be familiar to most students. Nonetheless, it is poignant to note that many students admitted that they did not know how their group product worked. A voluntary end of course survey, completed by 388 (92.4%) of the students, indicated that over 70% had no prior sketching or CAD experience. Response to the mechanical dissection project was 84% positive. Students indicated a greater than 60% increase in motivation to continue to study engineering. One student wrote: "It was a demanding but very rewarding project since it utilizes every aspect of the course and shows you what engineers must do to create parts. I had no previous drafting experience but after working through this course I feel confident in my ability to create parts through the three stages of design. This project and course are probably the most important part of first year engineering." After the January – April 2008 offering, a seven team PACE [20] playoff presentation was made in front of an industry judging panel that rated the winning group as being of equal calibre to recent engineering graduate hires.

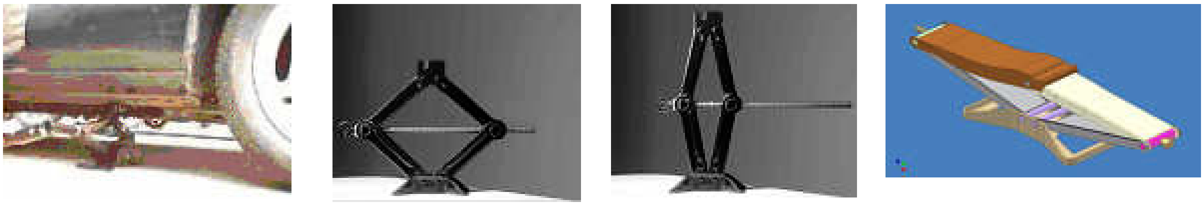
4.2 Second Year Mechanical Engineering

A successfully implemented project for second year students is design of an automobile spare tire changing jack. An ASME standard exists [21], and provides design specifications. Jacks are now usually placed between the wheels (Fig. 3(a)), and operate using an ACME screw thread and scissors style mechanism (Fig. 3(b,c)). The geometric CAD design of such a device (Fig. 3(d)) is rather straightforward, and approximate dimensions can easily be obtained from



mouse Polisher camera Lantern

Fig. 2: First year CAD mechanical dissection models.



(a) (b) (c) (d)

Fig. 3: Automobile jack example: (a) lifting location; (b) lowered position; (c) raised position; (d) CAD model.

student owned automobiles. This automatically provides variety to reduce copying. For students without cars, extra jacks can be obtained inexpensively from supply stores or auto wreckers.

As with first year, emphasis is more on analysis of the product, rather that creation of original work. The addition for second year is strength and mechanical element analysis. Without requiring extensive detail feature modeling, the geometry is drawn in CAD, including the ACME screw, nut, and revolute joints. Using a mechanism solver, the free body diagram forces are simulated and compared to hand calculations. A check for shear, crush, failure of the screw/nut and joints is expected, plus a buckling analysis of the beams. Simple finite element analysis is expected for the top platform, bottom base, and handle.

4.3 Upper Year Mechanical Engineering

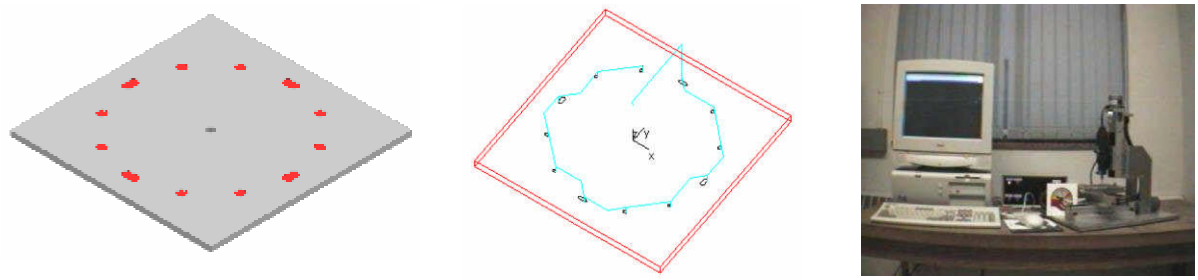
Upper year mechanical implementation of the curriculum has first been introduced into a new product design course. A subsequent upper year CAD course is being converted to emphasize assemblies, mechanisms, and sculptured surface design.

4.3.1 Product Design Course

4.3.1.1 Curriculum

Tab. 2: University environment fundamental attribution error observations

"You" style blaming	**"I" style ownership**
You made the test too hard.	I didn't do well on your test.
You cheated on this assignment.	I'm concerned about the originality of your assignment.
The second year students don't pull their weight.	How can we include the second year students?
The third year students don't include us.	How can we participate with the third year students?



(a) (b) (c)

Fig. 4: CNC machining example: (a) solid model; (b) tool path planning; (c) Dremel® tool and stepper motor based online machine.

The beginning of the product design course was used to test introduction of EI, with only a three percent component awarded for an in-class quiz. Technical course material is based on the Ulrich and Eppinger [22] text, supplemented with custom rapid prototyping and CNC machining notes. Students work on individual product ideas that could be CNC machined or plastic injection molded. Major milestones include: 1) writing a product mission statement; 2) product concept generation; 3) peer concept evaluation; 4) product concept selection; 5) CAD submission to TA/instructor/technical staff for review; 6) CNC machining or rapid prototyping; 7) testing; 8) reflection and opportunity to iterate the design in CAD; 9) final report submission. Experiences with each milestone are summarized below.

Product mission statements were one sentence descriptions intended to begin the process of "freezing" [23] the design. Examples have included:

- "Wind-it-Up will be a hand-powered winder that is designed to wind a boxing hand wrap into a tight roll."
- "Holdilocks will offer an easy to use system to store both U and cable locks on almost any part of a bike frame."

Product concept generation provides an ideal opportunity to emphasize Qualify Function Deployment (QFD) [24] and voice of the customer "what to solve" thinking, as well as avoidance of prejudicial selection of a known (and hence not innovative) solution. Students are required to review current market offerings, and search for related patents. Corresponding lectures introduce use of Theory of Inventive Problem Solving (TRIZ) [10] "how to solve" principles.

The peer concept evaluation activity required the concept author to meet with two other students to explain the product. These two students then acted as peer evaluators to provide constructive feedback to the author.

Detailed CAD/CAM/CAE work next takes place. A professional level of FEA analysis is expected to confirm suitable strength, snap fastener and intended flexibility features, etc. Design for CNC machining or injection molding requires significant attention to detail.

Draft angles are not required, but thin, equal thickness walls are expected. Decisions must be made on whether undercuts should be handled by separating the part into pieces. Design tips [25] were provided to assist students. Before CNC machining or rapid prototyping occurs, TA/instructor/technical staff approval must again be received.

4.3.1.2 Example Projects

To illustrate course curriculum with circumstances familiar with students, design of suite of desktop accessories was presented. The idea is to provide a cable organizer, LCD monitor mount, in/out baskets, clock, study lamp base, etc. The solution backbone uses 80/20® aluminum extrusion [26] that is clamped to the rear of the desk. The company website provides CAD models of the extrusions, fasteners, etc.

The clock example uses Gravoply 1® engraving plastic [27]. The clock face is first drawn as a solid model (Fig. 4(a), and the CNC tool paths are created (Fig. 4(b)). The tool paths are verified offline using an in-house developed ACIS®

based [28] Boolean subtraction program. The online version drives a Dremel rotary tool [29] based stepper motor CNC machine (Fig. 4(c)) [30].

Detailed design of a classic, spring balanced arm study lamp base is discussed in the lectures (Fig. 5(a-c)). The base is intended to first be made from ABS plastic using the Dimension BST [31] 3D printer (rapid prototyping) machine available in the department. The part is first drawn as a solid, and then modified to a thin wall shell. Estimated forces from the lamp are specified and FEA analysis, using software included with the CAD system, is carried out. Students are challenged to optimize the strength to weight ratio in a graded assignment before proceeding with detailed CAD design of their own product. An aluminum LCD NEMA monitor holder (Fig. 5(d)) is also discussed.

Other representative projects include an iPod® ear bud holder (Fig. 6(a)). The idea is to place the holder between the purchased iPod® device and belt clip in a piggy back fashion. This illustrates the TRIZ mediator concept (inventive principle 24). The bug vacuum is intended for use as a household central vacuum attachment for removing small insects from walls. The tubular shape of the item cannot be made in one piece, and lectures discussed the choice between splitting into mirror image halves (as is common for electric hair dryers, drills, etc.), and the easier to seal design shown in Fig. 6(b). Sometimes students bring forward a design that is intended to mate with the complex surface of an existing part. For example, Fig. 6(c,d) illustrate addition of stabilizer arms, so that loud music can be played without loosening the rear view mirror. A laser digitizer was used to capture two cross sections on the existing mirror. The point cloud was thinned using least squares, and imported into the CAD software to create the mirror model. The stabilizer arms were then added, and rapid prototyped.

4.3.1.3 Discussion

Instructor experiences over the two years that this has been included suggest that the EI material isn't proactively retained unless there is regular reinforcement. This was accomplished by briefly discussing current events, such as security incidents at Phoenix [32] and Vancouver [33] airports, at the beginning of lectures. One particularly "teachable moment" opportunity arose when a student at first wanted to file a complaint against a TA. By asking the student to consider Covey's [34] Habit 5: Seek First to Understand, Then to Be Understood and Habit 4: Think Win/Win, the complaint was quickly withdrawn. It is difficult to measure teaching impact with this topic, since success comes more from the lack, rather than the presence, of conflict. Towards the end of the course, and in the following months, students would sometimes wink in recognition of an example where EI was or was not being displayed. Tracking this beyond graduation, with the assistance of the campus career services office, is proposed.

Many students have great difficulty in narrowing down the selection of a product to develop. This problem has been observed in society [35], and hence it is necessary, even for this upper year course, to provide explicit acceptance criteria. Design constraints must include linear dimension (<20 cm), rapid prototyping machine plastic volume (<100 cm^3), material (ABS plastic plus fasteners, etc.). A short Stage-Gate® [36] style meeting with the TA/instructor is held to confirm appropriateness. Students often have an underdeveloped sense of scale, and limiting product size is essential to later avoid prototyping cost overruns.

The first time the course was offered, authors were asked to select their own evaluators. Students didn't really know everyone, and the TA/instructor sorted out unmatched cases. The second time, authors and evaluators were matched up randomly. This was poorly received, as evaluators were shy about giving feedback to authors who were not their friends. The planned compromise is to first allow students to select their own evaluators. Unmatched cases are completed with TA/instructor assistance. During the in-class evaluation periods, the TA/instructor works to overcome shyness with these latter groups.

Because of experience in earlier courses, students are able to create conceptual CAD models with high success. The difficulties come in the details, thin wall design, and strength analysis. The most common machining issues were designing with sharp internal corners (failure to account for the tool radius), or designing a non-manifold solid model (that the tool path planning software would reject). Rapid prototyping issues include direction of build, support material removal concerns, dividing into several parts and gluing together, choice of fasteners, etc. TA/instructor/support staff approval, and advance payment of the prototyping cost, is required before parts are actually made. Depending on demand, wait time has been as high as three days.

Seldom does a design work out correctly the first time and students, who often have an elevated sense of invincibility, are humbled to experience this. Grades are reduced for products that do not correctly function, but an opportunity to correct design faults in CAD before submitting the final report, and recover some credit, is offered. Inclusion of this step really "drives home", in a practical and real world way, the escalating time and money cost of iteration during the later design stages. Providing iteration opportunity requires that the project due date be set approximately three weeks before the end of term. Lecture attendance is maintained by covering detailed theory during this period, in preparation for the final examination.

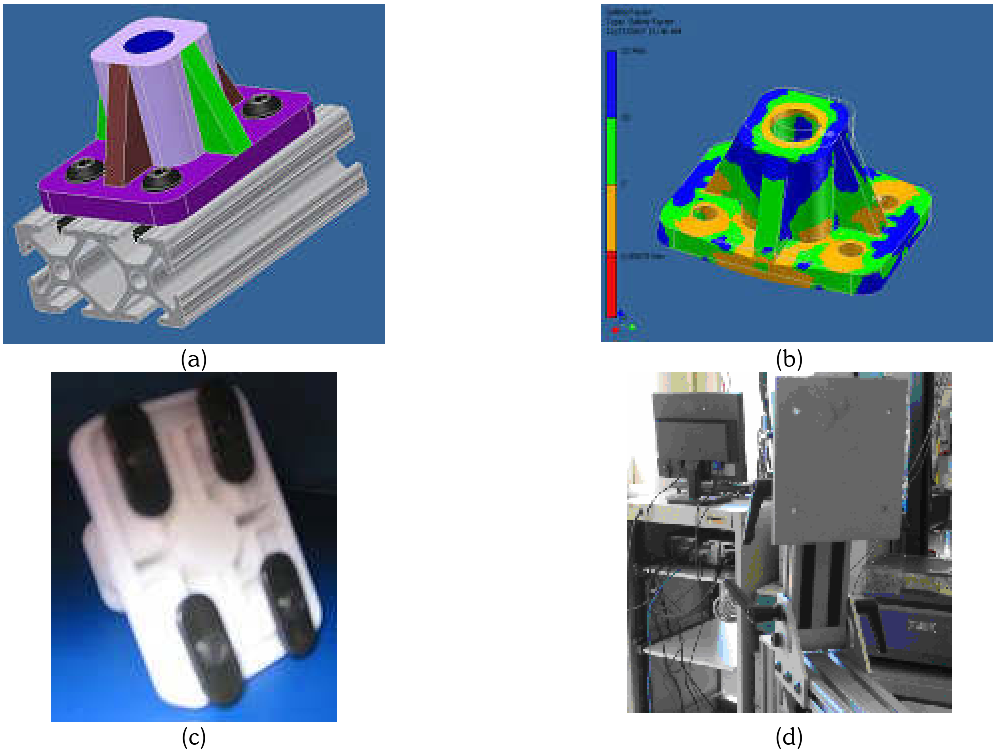


Fig. 5: Product design course examples: (a) 80/20® extrusion and ABS plastic lamp holder (CAD); (b) FEA analysis of lamp holder; (c) photograph of rapid prototyped lamp holder; (d) photograph of LCD NEMA monitor holder.

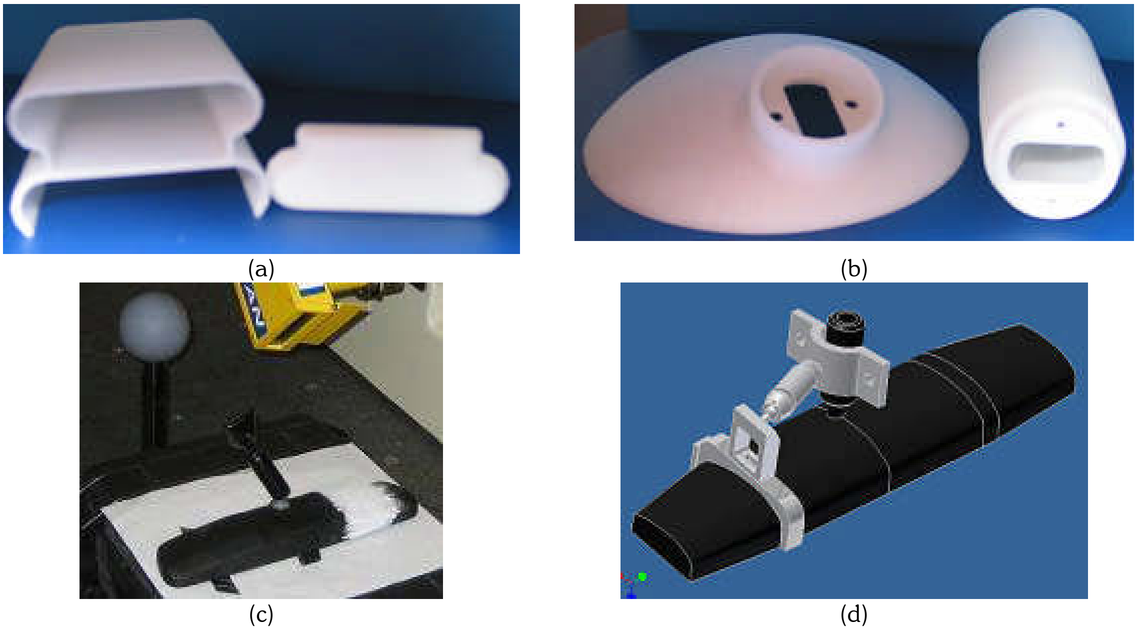


Fig. 6: Product design course examples: (a) iPod® ear bud holder; (b) central vacuum bug attachment; (c) automobile rear view mirror laser scanning; (d) automobile rear view mirror holder stabilizer (CAD).

4.3.2 Advanced CAD Course

With the introduction of 3D modeling in first year, and the product design curriculum initiative described above, the existing subject based CAD course must now be revised. Based on the growing capabilities of software, the chosen directions were expansion of assemblies, with particular emphasis on kinematic and dynamic mechanisms. Sculptured surfaces and B-splines were expanded as well. Reverse engineering coverage includes laser digitizing, least squares data fitting, and homogeneous transformations. Completed projects are converted into VRML, and displayed in a dual projector polarizing filter based 3-D theatre, as well as on the course web site. Again, the project submission date was moved to approximately 3 weeks before end of term. Advanced lectures of B-spline mathematics, mechanism solution theory, etc. were delivered during this period to prepare students for the final examination.

For future years participation of CAD vendor and industrial judges, in a manner similar to the first year course, is planned. The course is also offered to graduate engineers through the multi-university Advanced Design and Manufacturing Institute [37]. This initiative provides additional industry interaction to ensure that academic course topics are aligned with current industry needs.

5. CONCLUSIONS

This paper has described curriculum revisions from first and second year courses in mechanical dissection, solid model creation and FEA analysis, to upper year original product design and manufacturing implementation. Initial experiences anecdotally suggest improved student motivation and co-operation. Because the tasks and workflow are more unstructured than familiar course assignments, regular milestones must be set. If set early enough, the milestones provide an opportunity for revision of poor submissions. This increases accountability that would otherwise be lost due to end of term time constraints. Early milestones are also essential to avoid contention for resources such as the rapid prototyping machine, CNC mill, etc. Emotional Intelligence provided students with a greater awareness of the causes of team conflict. Actual products provide students with more developed sense of scale when working in CAD, and the prototypes allow them to take away more tangible results as they graduate to the workforce. Project judging by an industry panel added additional relevance and enthusiasm. Improvements in both team work and design skills are very difficult to quantitatively and immediately assess. To address this, and within the boundaries of privacy laws, the authors plan to continue monitoring through final examination performance, subsequent courses, Canadian Engineering Accreditation Board evaluation, co-op work term employer evaluations, and beyond graduation.

6. ACKNOWLEDGEMENTS

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