AC 2011-2803: REDESIGN OF OUTBOARD MOTORS FOR USE IN THE GRAND CANYON

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Introduction

This paper details a two-semester design and build project accomplished by senior engineering students from the College of Technology and Innovation at Arizona State University. These students worked with students from two other institutions engineering programs (Northern Arizona University and the University of Utah) on a set of design and build problems funded by the Grand Canyon River Outfitter's Association (GCROA) with support from the National Park Service (NPS). This organizational structure reflects a primary objective of the capstone experience at the College of Technology and Innovation; to provide, in a project setting, an educational experience consistent with professional practice. Student motivation was increased as this project was part of a larger effort to enhance the environmental aspects of float trips through the Grand Canyon. Thus, the curricular design "flavor" of the project is consistent with recommendations from several recent engineering educational studies[1,2] Such reports urge the adoption of curricular mechanisms that include practice-like experiences, including both design and prototyping, which are connected to important issues within society.

However, such projects often make individual evaluation and assessment of the student's educational performance a hard task. Evaluation of student educational objectives is essential in ensuring an engineering education program is producing qualified and competent applied engineering professionals, whom can make substantial contributions to their employers in as short a time as possible. Such feedback is important in the ABET accreditation process. This paper provides a brief overview of the assessment system used to assess student teams in this practice-based environment.

Capstone Course Approach

The College of College of Technology and Innovation at Arizona State University strives to fully embody values of engaged learning, use-inspired translational research, deep engagement with industry, and entrepreneurship. The academic facilities were designed specifically to support the polytechnic learning and discovery environment. The College is home to innovative engineering education programs, including a multidisciplinary engineering program and various engineering technology programs. Students in these programs are taught prototyping skills in advanced, state-of-the-art learning laboratories.

Most capstone projects are funded by an industry partner, thus student projects have an industrial flavor and a budget to support the design and prototyping phases. Faculty and students interact with industry partners and this approach has positive outcomes as it allows students to work on real problems, guided by experienced faculty members and industrial partners. To support these company sponsored projects, a set of guidelines regarding budget and intellectual property have been established. The sponsor creates a proposal, including a brief problem statement and budget.

Once a project is established, they are staffed with a multidisciplinary student team. Students come from the two different departments, the Department of Engineering and the Department of Engineering Technology, and represent four different engineering disciplines (mechanical, electrical, manufacturing, and civil). On the first day of the capstone course, all students listen to short, five minute presentations on each project. After these presentations, students are given a short skill-set survey asking questions about their skill sets. The students also turn in project list where they rank the top five projects they would like to work on for the year. The department chairs and capstone coordinators then review the surveys and student project interests to staff the project teams. A large majority of students are placed on one of their top three project choices.

The capstone sequence primarily takes place in the fall and spring semesters. During the fall semester, the projects are staffed; teams develop a complete problem/project description, develop a project schedule, and complete a formalized design process to select a solution to the problem. During the second semester, the students do detailed design of their chosen solution, create a manufacturing plan (make/buy decisions and component manufacturing), and complete a professional level prototype. Deliverables include an extensive design report, engineering drawings and the prototype.

Staffing teams with students from a variety of engineering education programs with distinct skill sets yields significant benefits for both the students and project solution quality. In addition to the mix of technical skills, the students have a mix of professional skills. One program emphasizes the process of design in their courses, and those students tend to lead the project teams in the early stages of the project. Student from other programs have stronger component design skills and they gravitate into leadership roles during that phase of the project. Other students have strong manufacturing skills and they become leaders during the prototyping stages. When combined, these skill sets produce spectacular results in a project-based setting. In fact the deliverable from past capstone projects have industrial partners waiting in line to be involved.

Lower End Capstone Project Overview

The Grand Canyon River Outfitters Association (GCROA) is a non-profit trade group based out of Flagstaff, Arizona. The GCROA has funded a multi-year project set, involving up to four Universities, focused on reducing the environmental impacts on motorized float trips through the Glen and Grand Canyons. An important environmental consideration was noise. Thus, in the first year of the effort, electric motors became a primary solution mode. Also, data from the GCROA indicated that the outboard motor lower ends, designed for much less rigorous use than seen in the Grand Canyon, often were damaged. Thus, in the second year of the effort, the GCROA funded two Universities to design and build prototypes of a much more robust lower end, which also were adapted for electric motors.

All of the outfitters providing motorized float trips in the Grand Canyon use the same basic watercraft powered by a four-stoke outboard gasoline motor, supplied either by Honda or Tohatsu. These engines average of four to six hours per day on a normal trip and burn approximately 60-70 gallons of gasoline per trip. GCROA's move to four-stroke motors in 1997 was a large step in their effort for a more environmentally and customer friendly experience. As part of its new ten year plan approved by the National Park Service, the GCROA agreed to fund an effort to develop, test, and implement alternative propulsion technology suitable for commercial riverboat operations on the Colorado River[3]. To support this effort, on January 1, 2008, the National Park Service (NPS) supported the work as part of the *Centennial Initiative*, as shown in Appendix A.

As a result of the first year's efforts by various capstone teams across four Universities, the GCROA decided that an electric motor would be a power source investigated further. However, due to the long term issues with conventional outboard lower end (all parts of the outboard motor below the power head) durability, GCROA funded two different schools to design a "hardened" lower end that would be compatible with the selected electric motor (which saw continued development work by other teams). The ASU capstone team's project was to design a durable, reliable, and easy to maintain lower unit. This was a unique opportunity to redesign the lower end to withstand the unique river conditions of the Grand Canyon. The major problems the outfitters encountered with the regular lower ends were strength/ durability issues with the shafts, propellers, water pumps, and woodruff keys in the lower end. Other areas the outfitters wished to improve upon during the lower end redesign were; required maintenance, impact survival, and ease of assembly and disassembly on the river and in the shop with minimal tools. One advantage of the electric motor as the power source is that it could be reversed, removing the need for the lower end to include a reverse shift and gearing mechanism.

Fall Semester Design Process

Once the lower-end design (LED) student team was announced, the team assembled and was comprised of two multidisciplinary engineering (EGR) students, four mechanical engineering technology students and two manufacturing engineering technology students. Given their extensive background in a formalized design process, the EGR students assumed leadership and led the first semester's design stage. The students began by creating a Gantt chart which outlined their schedule for the design semester. This gave the students a firm timeline to adhere to and it also served as a tool for the faculty member for assessment of individual and the group project performance. The Gantt chart broke down the design stage project process into individual and team tasks along with a time allotments for each task. The Gantt chart motivated the students to keep the group on schedule and puts the allotted time into perspective, which ultimately helped the young engineers meet the critical project deadlines.

Identification of Project Constraints and Criteria. After determining the project schedule, students began identifying preliminary constraints based on the project description provided by the GCROA and NPS. This included formulating a budget for the project, which was one of their constraints, where a constraint was something which must be met by the design in order for it to be a feasible solution. Not meeting a design constraint means the concept is not a viable solution. A design criterion has a range of values and may have different levels of importance. The design constraints and criteria were used to rank different design concepts. Once several design concepts meeting the constraints were developed, they were ranked according to how well they fulfilled the criteria.

Students developed the initial project constraints for the project before traveling to visit and survey the customer i.e., GCROA outfitters. Table 1 shows the project's criteria and constraints.

Table 1. GCROA Capstone Project Criteria & Constraints

Constraints	Criteria
1. $5000.00 budget	1. Least possible time for assembly
2. Designed by end of fall semester	2. Least possible time for Disassembly
3. Built tested by end of spring semester	3. Longest possible time before parts replacement
4. Must use current mounting system of outboard motors	4. Housing water intake over time (Or pressure) adequate
5. Must allow for water cooling of the motor	5. Highest possible toughness/strength
6. Must tilt	6. Least possible amount of air produced by propeller
7. Must have enough thrust	7. Temperature of engine remains as low as possible
	8. Motor Angle Range as large as possible
	9. Parts available by fewer suppliers
	10. Number of tools needed for assembly/disassembly as little as possible
	11. Size of motor as small as functionally possible
	12. Weight of motor as little as possible
	13. Cost of motor as little as possible
	14. Thrust after rock strike as high as possible
	15. Hours/cost/amount of new parts needed for repair as little as possible
	16. Number of parts as little as possible
	17. Time it takes to take motor off as little as possible
	18. Highest possible number of different current props in use able to attach
	19. Least possible pollutants ejected over time
	20. Least noise emissions possible
	21. As safe as possible

Research and Baseline Existing Design and Specifications. After identifying the initial project constraints and criteria, the students did a base line study of existing design. In part, this work was to make sure their lower-end design would meet if not exceet the current 30 HP Honda motor's specifications. The main aspects the students wanted to match were the thrust of the motor, its torque at the prop, and its rotations per minute at the prop. If the new design did not feel as powerful if not more powerful the students felt the outfiters would not accept the alternative powered outboard motors.

Define Customer Needs. The next step in the lower-end design was to define the customer's needs. This proved to be difficult because the students did not have direct contact with the outfitters, many of which were located in northern Arizona and southern Utah. In order to get an idea of what the outfitters were looking for in an improved lower-end design, the students decided to create a survey for the GCROA members. The questions were designed to give the lower-end design team a better understanding of what the outfitters considered a problem with the current lower-end design, and what the most common modes of failure were for the current lower ends. Along with negative design aspects, the students also asked the outfitters what they liked most about the current lower-end design and what they would like to see improved or added. This gave an opportunity for the customer to voice their opinion and the students could retain some of the postive aspects from the current design in their prototype.

When the students received the completed surveys, they tabulated the results to create a list of customer needs. These were as follows:

Easily asembled and disassembled;
Low maintenance;
Water-tight lower end;
Withstand impact;
Accessable water pump;
No cavitation;
Cooling for the engine;
Adjustable transom angles;
Uses available parts;
Be able to repair in the field;
Use the same mount size;
Can not weigh more than the current lower end;
Can not exceed the curent cost of the outboard motor; and,
Must have control.

The needs list from the customer surveys gave the students a better understanding of what the GCROA outfitters wished to see in the new lower-end design. Finally, the students found room in their budget to travel to Page Arizona and meet with the outfitters after surveying them. This allowed the students to get a feel for the customer needs they had researched and prioritize/rank the needs in order of importance.

Through the comprehensive design process described above, the students established a list of customer needs. The needs were used to define the outcome of the design since the ultimate goal was to satisfy the customer's needs. But, there were two things needed to be done before the customer's needs could be used for the LED. The design team had to rank the needs and develop metrics from them.

The students used a team-based process to prioritize the customer's needs. Each team member individually ranked the needs. The student ranking was based on their experiences with the customers. Table 2 (next page) shows the results of the individual team member rankings, the added total, and resultant weight associated with each need. The weights found for each need dictate that needs level of importance, and will be used later in the design process to ensure that the design takes into account what is most important to the customer.

Metrics and Product Specifications. Developing metrics was the next task. Metrics were essential to the design because they were used to evaluate the designs. Metrics are numerically quantifiable measures of the customer's needs. Ideally, there should be a metric for every individual need to be able to guarantee a design has met the customer's need. The students went through every need and created a metric until they had a comprehensive metric list sufficient to evaluate their proposed designs. As it was a comprehensive set of metrics, this Excel file grew to be quite large and is not shown here.

Once metrics with quantifiable values were developed, the team had to establish desired target value ranges for their new design. These target values for metrics are known in industry as product specifications or engineering requirements. The engineering requirements were target values established to evaluate whether the design sufficiently met requirements. The resulting large data table of the LED engineering requirements was also created using Excel.

Functional Decomposition. The next step in the process was to generate a functional decomposition and create a quality function deployment (QFD). The students performed the functional decomposition by taking the current commercial lower end design, dissecting it piece by piece, and determining the function of every part and its contribution to the assembly. The goal of this process was for the students to determine all of the functions the outboard motor lower end must perform, allowing them to determine which parts were needed or could be eliminated. This process insured that the new lower-end design could perform all of the functions needed by the outfitters. The students broke down the functions into major assembly and sub-functions. Once the major and sub functions were determined, they were used in a QFD matrix. The QFD matrix was a spreadsheet used to determine the function's importance by ranking it against the product's metrics, using a similar system as the needs-metrics matrix.

Design Solutions Table. Once the students determined the functions and charted the products metrics versus the products functions, a solutions table was created. The solutions table contained a list of all the possible solutions or ways of performing the function. To make the solutions table, the students looked at every function found during their functional decomposition. They brainstormed and listed every possible solution they could think of that would be able to perform that function. Every brainstormed solution for each function was placed into their solutions table. When the solutions for every function are combined, the result is a product concept. The product concept contains a way to perform every function required. Since the functional decomposition identified all of the functions the lower end needed to perform, a solution combining all the functions forms a complete product. Again, the solutions table was a large Excel file that was broken into the various functional requirements.

Table 2. Ranking of Customer Needs

Needs Importance	Ranked 1-22 with 22 being the most important									
Need	**Individual Ranking**								**Total**	**Weight**
Easily assembled and disassembled	19	22	21	17	19	13	15	17	143	0.070305
Low maintenance	16	21	18	19	20	15	22	15	146	0.07178
Watertight lower end	9	20	17	8	15	16	14	19	118	0.058014
More durable lower end	22	16	22	21	22	20	21	20	164	0.080629
Withstand impact	21	15	20	22	14	19	20	22	153	0.075221
Adjustable transom angles	3	3	1	10	6	13	6	5	47	0.023107
No cavitation	17	6	4	16	11	6	7	8	75	0.036873
Engine must remain within operational temperature	10	14	8	15	7	17	13	16	100	0.049164
Uses available parts	5	5	19	9	12	5	5	14	74	0.036382
Be able to repair in the field	12	7	13	14	18	12	19	18	113	0.055556
As small as possible	7	2	6	4	9	4	4	6	42	0.020649
Weighs as little as possible	11	1	7	13	10	2	3	11	58	0.028515
Costs as little as possible	6	9	11	3	8	1	2	9	49	0.02409
Easy reparability	20	13	14	20	21	14	17	21	140	0.06883
Adequate thrust to get to shore after rock strike	8	10	12	18	5	18	18	7	96	0.047198
Limited number of parts	15	4	16	2	17	7	12	13	86	0.042281
Be able to swap failed parts in field	14	8	15	7	16	10	16	12	98	0.048181
Able to dismount motor easily	4	11	9	5	13	11	11	10	74	0.036382
Clean to the environment	18	17	3	11	2	21	8	1	81	0.039823
As little noise as possible	2	18	2	12	1	8	10	4	57	0.028024
Safe System	13	19	10	6	3	22	9	2	84	0.041298
Highly adaptable to various current props	1	12	5	1	4	9	1	3	36	0.017699
									2034	1

Create Concept Combinations. Creating concept combinations involves ranking the solutions, reducing the number of solutions for each function, and then combining the top solution for each function to form a concept. First, the students individually ranked each functional solution based on how well the solution would perform an associated function. The scores for each team member were then averaged together to determine an average score for each solution. Weights for each function determined by the QFD matrix were multiplied by this average score to form a weighted averages solutions table. This mechanism provides a linkage between customer needs and solution choices. The overall design process employed by the capstone team is depicted in Figure 1.

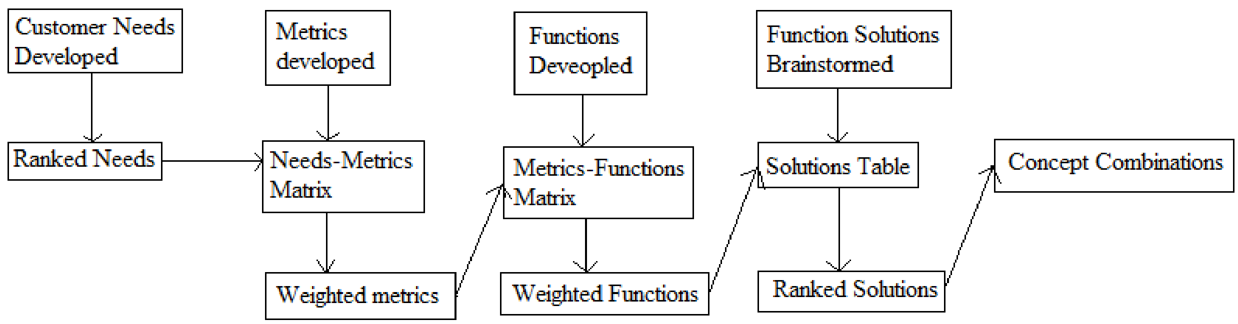

Figure 1. Overview of Lower-End Design Process

Solutions were eliminated if they received a low score by a comparatively large margin. This is where unreasonable brainstormed solutions are removed from consideration. Although some solutions were ridiculous, they were still included in the ranking process to avoid any closed-minded design decisions. Figure 2 shows an example of one of the design solutions brainstormed for the lower end, which was quickly removed from serious consideration.

The students combined values and created a concept variations table. This table included a total of 72 possible concept combinations (out of a possible 9.6 x 10^{14} possible combinations involving all of the brainstormed solutions). Each of these 72 concept combination was ranked by adding together the weighted scores of the solutions within that particular design combination. From these 72 solutions, the top four solutions were selected and investigated via a preliminary design process.

Figure 2. Belt Drive and Wood Barrel Covering the Electric Motor

Final Design Solution. After three-quarters of the fall semester, students were done with the initial design process and began doing preliminary design of the top four solution sets: a hydraulic system, a belt drive, a flex shaft drive and the top ranked solution, a solid shaft drive. After the preliminary design process, and design review with the faculty mentors, the students chose the use of two solid shafts to transmit power from the motor to the propeller. While similar to the existing, commercially available lower ends, the student design included several key features. Each of these features is discussed in detail below.

Spring Semester Design Process

The team decided to create the entire assembly in Solid Works™.   In addition, this was the point in the project where the leadership roles started to shift from the multidisciplinary engineering students to the engineering technology students.   The mechanical engineering technology student led the solid modeling, machine design, manufacturing and assembly teams with the other students providing design support.   Several features of the design are discussed below.

Motor Mounting. The University of Utah, tasked with the motor and systems design, had chosen the power unit to be a Lynch Motor model LEM-2x2-D135. Thus, the ASU students had to provide a motor mount on their lower end design. But, the ASU students also wanted to make their lower end design compatible with a wide range of possible electric motor combinations, as well as make switching motors easy for the outfitters, especially if a switch needed to be done while on the river due to a breakdown. With this design constraint in mind, the students engineered a solution utilizing a flat plate bolted to the electric motor and connecting to the new lower end design via an interlocking ring and hub mechanism. The motor bolts directly to the flat plate, using existing mounting holes in the motor, and the plate is held on by a lock ring mechanism which does not require tools to operate. The ring slides over the head of the mounting bolts, allowing the bolts to slide in the slots, and a detent pin holds the ring in place. A visual representation of the student's motor mount via a Solid Works solid model is in Figure 3.

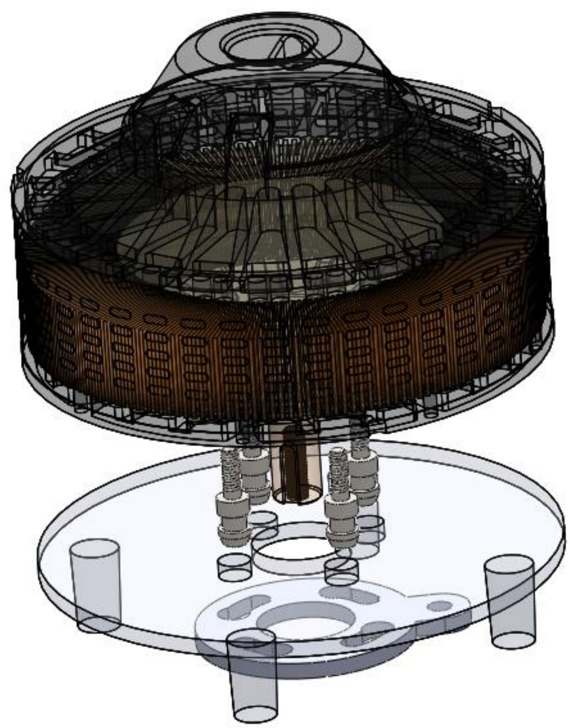

Figure 3. Modular Motor Mounting Lock Ring Plate

Clutch Design and Analysis. The student's shaft design included a torque-limiting clutch to mitigate the risk of a torque overload in the drive system. Based on the specifications provided by University of Utah for the motor's maximum torque, an adjustable torque limiting clutch was specified. A clutch, in Figure 4, produced by Mayr was selected[4]. This clutch did not require regular lubricant changes, which reduces maintenance, and automatically reengages after disengagement. The clutch provided protection of both the motor and the drive systems in case of the propeller striking a rock or a sand bar—common causes of failure in the Grand Canyon.

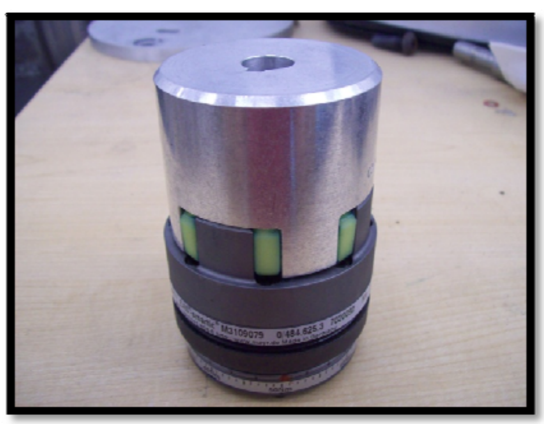

Figure 4. Torque Limiting Clutch

Housing Design and Analysis. The design of the external case was a complex task as the case both supports the mechanical systems of the power head and lower end, as well interfacing with the water/boat steering systems. The design's profile had to be hydrodynamic and provide a standard mounting system to the boat. Many of the repair features of the conventional outboard motor case liked by the GCROA members were maintained in the new design, along with increased river survivability. Figure 5 shows aspects of the shaft design.

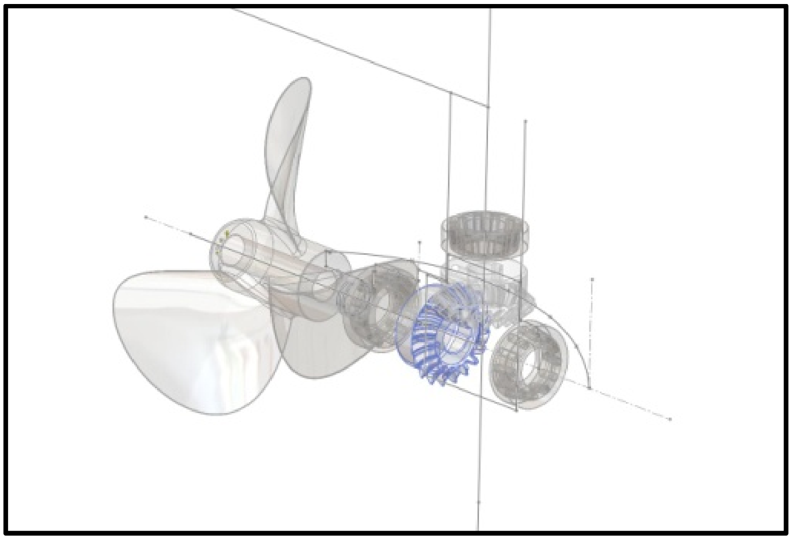

Figure 5. Vertical & Horizontal Shaft Assembly

Stress Analysis. To validate hand calculations and final design, finite element analysis software was used on various parts to confirm their ability to withstand the loads expected while under operation. Using NX 7.0*TM* software, the tiller mounts, vertical and horizontal shafts were analyzed for the stress and displacement. Figure 6 (next page) is an example FEA result for the tiller mount. FEA results were compared to student calculations and were found to match the calculations for displacements and stress.

Manufacturing & Testing

A requirement of the College of Technology and Innovation capstone project methodology, students teams create a professional prototype (a rendering of the final design is shown in Figure 7 below). The first step was to create a new Gantt chart for the manufacturing, and testing stages. This schedule mechanism was used to assess student performance and keep the team on track to meet their deadline for testing on the water in May.

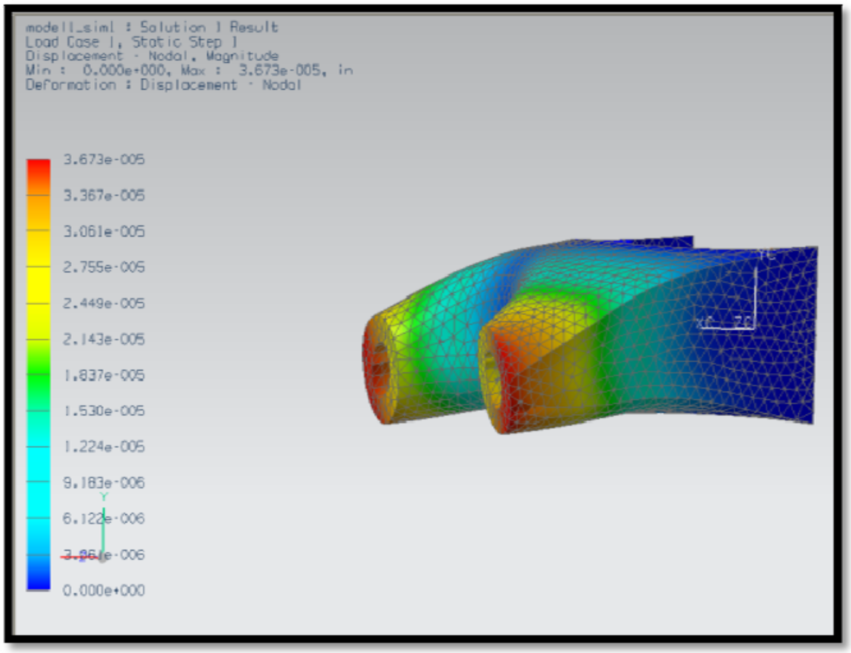

Figure 6. Stress Analysis of Tiller Mount

Figure 7. Solid Works Rendered Final Assembly

Engineering Drawing Packet. The students had to use their solid model to create an engineering drawing packet for the manufacture of the parts. The mechanical engineering technology students created the prints from the solid model assembly and assigned tolerances so the components would fit when assembled. A sample student engineering drawings is pictured in Figure 8.

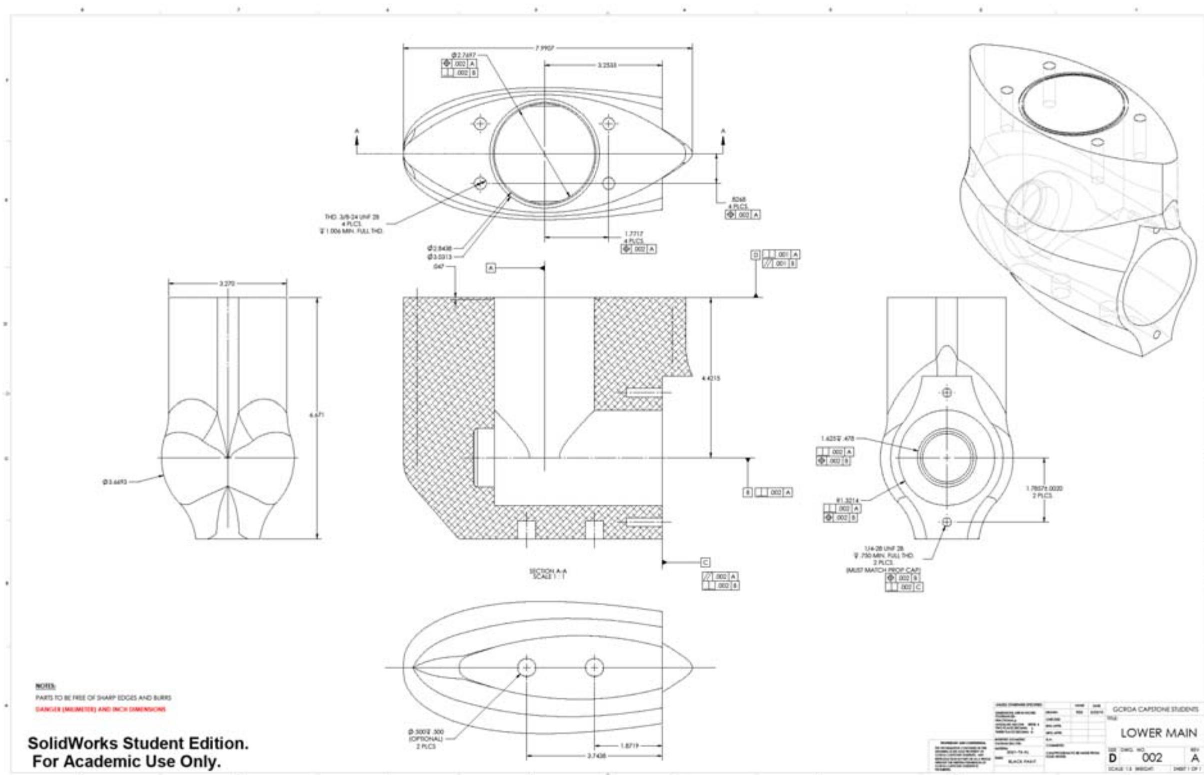

Figure 8. Sample Engineering Drawing

Raw Material Procurement. Once the engineering drawing packet was created, the students created a bill of materials. The bill of materials for the prototype is shown in Figure 9 below. The bill of materials allowed the team to determine which parts needed to be manufactured for the design and which parts could be purchased.

Bill of Materials

NAME	COUNT
1/4-28 x 1" PROP CAP BOLT (62196A329)	2
18mm SHAFT COLLAR (3369K220)	1
20mm GEAR (MMSA3-20R)	1
22mm GEAR (MMSA3-22L)	1
3/8"-24 x 5" BOLT (91251A475)	4
3/8-24 x 1-1/4 (91255A647)	4
5/16-18 SHOULDER BOLT (90298A622)	4
ANTI VENT PLATE	1
BEARING SEAT	2
GEAR WASHER	1
INNER SHAFT	1
LOWER MAIN	1
LOWER MOUNT BLOCK	1
MID SHAFT ADAPTOR	1
NEEDLE BEARING (5905K135)	1
NOSE BEARING (03062-03162)	1
O-RING (5577K39)	1
O-RING (5577K4)	1
OUT UP TUBE	1
PROP CAP	1
PROP CAP BEARING (4A-6)	1
PROP NUT (94205A290)	1
PROP SHAFT	1
QUICK DISCONNECT PIN (92385A072)	1
R & Co. PROP 1.6	1
SHAFT SEAL (13125K94)	2
SKAG	1
SPLASH PLATE	1
SUPPORT GUSSET	2
TOP 2 (FOOTBALL)	1
TOP PLATE	1
TORQUE LIMITING CLUTCH	1
UPPER MOUNT BLOCK	1
VERT SHAFT GEAR NUT (94945A225)	1
VERTICAL SHAFT	1
VERTICAL SHAFT BEARINGS (XAA32004X-YAA32004X)	2

Figure 9. Lower End Master Bill of Material

Manufacturing Processes. The students investigated options of casting and CNC-machining billet for the lower-end design prototype. Due to budget and time constraints, the team decided to manufacture the lower-unit from billet aluminum. Using the capabilities of the Engineering Technology Department's manufacturing laboratories; the students decided that they were capable of manufacturing all of the prototype parts in-house. Rather than go into detail of every step in manufacturing every part, the following touches on some key points of interest. The student team created manufacturing routings for every part. These routing helped the students plan steps taken to create the part and provide an overall understanding of how each part was created, explaining the tooling used, the cutting method used, and how long each process and final part took to produce.

Lower Main Housing. This particular part was the most crucial part in the design in terms of tolerances and dimensions. A team of four students worked together to program, fixture and machine this part. The lower main housing is where the vertical drive shaft meets the horizontal drive shaft. This part contains a bearing race deep within the part to support the horizontal shaft. This pocket needed to be very precise in order to hold the bearing, so very small steps and light cuts were performed using a 1.0" diameter, 8.5" long end mill. This part was machined in three operations. First, drilling and boring the holes through the top of the part was done. Then, after rotating the part 90 degrees counterclockwise, the bore and drill operations could be performed through the back of the part. Lastly, the part was contoured on one side and then flipped 180 degrees in the vise with the contour operation was mirrored on the other side. Both a rendered and final product are shown below. The lower main housing is bolted to the upper main housing section and a second part, the propeller cap is bolted to the back. This part was a huge learning experience for the students involved with creating it! Figure 10 shows the machined part.

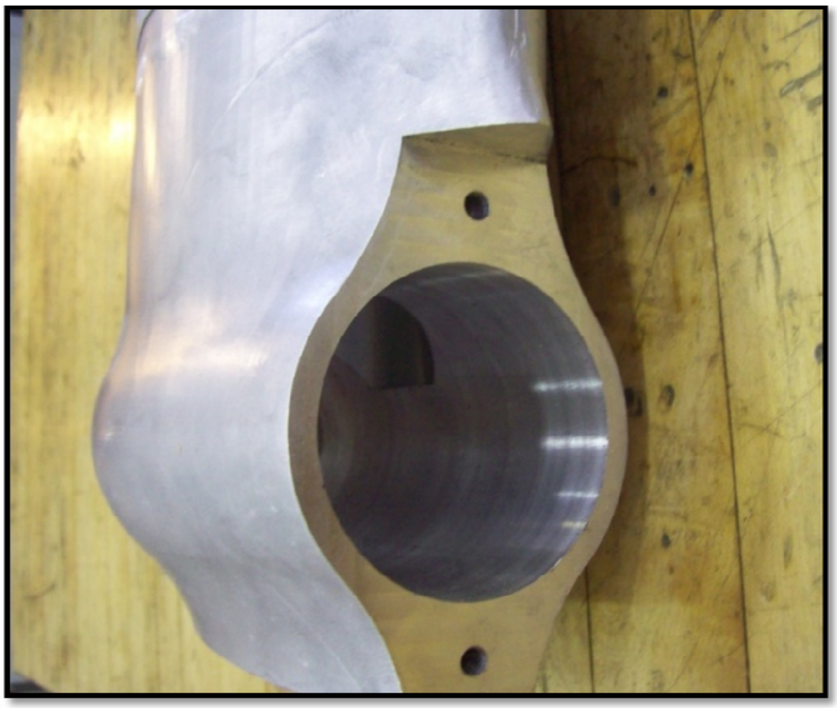

Figure 10. Machined Lower Main

Upper Main Housing. Another housing part, the upper main housing, was an easier part to make, with the exception of the helical threading needed in the upper half of the center bore. This threading was crucial because it is used to locate an inner tube, which contained the vertical shaft and related bearing seats. The inner tube is helical threaded approximately two thirds the way down the outside diameter of the shaft. The bottom of the tube locates within the bore of the lower main housing, securely aligning both main housing components. The machined upper main housing is shown in Figures 11.

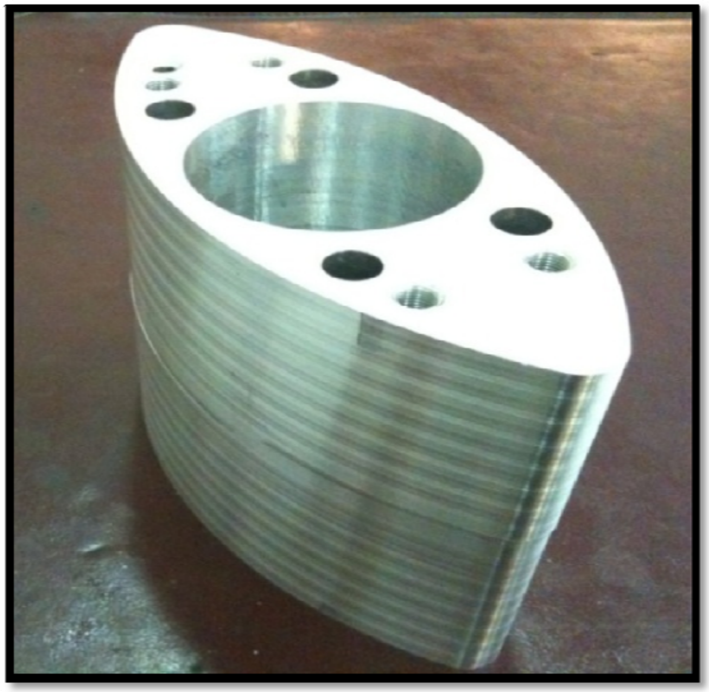

Figure 11. Machined Upper Main

Propeller Cap and Other Parts. The propeller cap, which bolts to the lower main to support the outer bearing of the propeller shaft, was machined via three-axis machining. The propeller cap is secured in the back of the lower main housing. This part was designed with an o-ring seal and supports the horizontal shaft and propeller. It also seals the gear oil lubricating the gears in the lower main housing. A number of other parts were manufactured by the students and included the anti-ventialtion plate, a three-axis part. It sits approximately 1.5 inches about the outer tip radius of the propeller and was welded to the upper main housing. The final product and a CAM programing screenshot are shown in Figure 12.

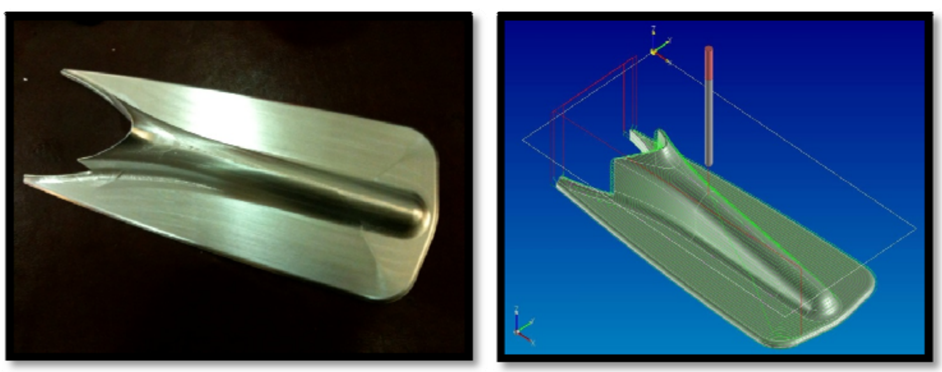

Figure 12. Anti-Ventilation Plate

The splash plate is the mounting plate for the outer tube. The outer tube is welded to the top of this plate; which when assembled, is bolted to the top of the upper main housing. The outer tube encases the inner tube as well as serves as the mount for the motor mounting plate. The assembled outer tub with the motor mounting plate is shown in Figure 13.

Figure 13. Assembled & Welded Outer Tube

Due to customer requirements and standardized propeller mounting, the students needed the splines on the lower end horizontal shaft to be the same as the splines on the Honda and Tohatsu propeller shafts. However, a spline cutter for these splines is not readily available. So, the students had a custom carbide cutting tool made to cut the spline on the horizontal shaft using four-axis programming. Figure 14 shows the cutting edge of the carbide cutting tool used to make the horizontal shaft splines.

Figure 14. Custom Carbide Spline Cutter

As mentioned earlier, the students designed and manufacturing an adapter plates to provide quick electric motor mounting on the lower-end. The manufactured assembly is shown below (the top plate shown is attached to the motor and the plate underneath is attached to the lower end).

Figure 15. Electric Motor Adapter Plates

The University of Utah student team was responsible for a motor cowling design. To provide an interface between the lower end and this cowling, a cowling adapter plate was also manufactured by the ASU students. The cowling plate bolts between the mounting plate and the adapter plate respectively. Having this cowling plate allows for the University of Utah cowling, tiller handle, and electronics to easily connect and adapt to the rest of the new lower-end, ensuring that all the electronic components did not become wet on the river. Figure 16 shows the model of the assembled cowling and motor adapter plates.

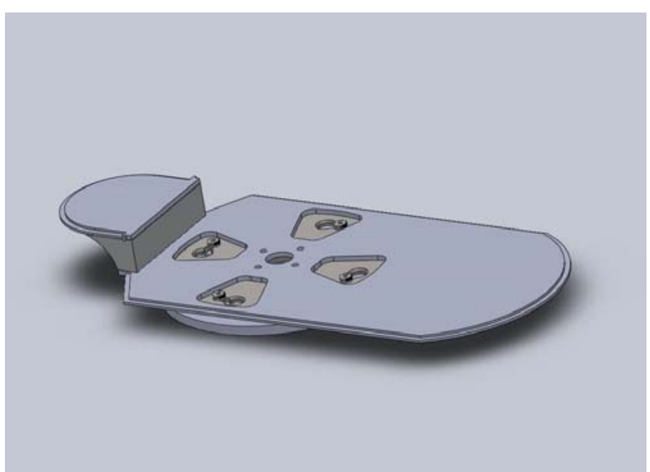

Figure 16. Cowling/Motor Adapter Plate Assembly

Another customer requirement determined during the design phase was that the stock Honda saddle and tiller setup would be used. Thus, mounting blocks were designed and machined for a direct interface between the stock Honda saddle and the new lower-end design. The mounts are welded to the outer tube and match the dimensions found on the current Honda lower-end. The finished mounts can be seen in the final assembly figure below.

The skag is the lower fin of an outboard motor assembly. The student design was intentionally much stronger than the commercial outboard motor skags. This was a request from the outfitters as the skag is often broken during a canyon trip. So the students designed it to take a rock strike. After machining, the skag is welded to the lower main housing of the lower-end.

Finished Assembly. The finished prototype of the lower-end assembly is pictured in Figure 17. A stock Honda propeller is mounted on the assembly. While machined from billet for the prototype, all external components were designed to allow an easy adaptation to casting as the manufacturing method, providing economical manufacture of larger quantities of the lower end.

Figure 17. Assembled Lower-End

Prototype Testing.

The final testing was done outside of Flagstaff, AZ. This was the first time that the ASU student team would see the University of Utah student team's electric motor drive system. Thus, to this point, all detailed design communication between had happened via email and CADD models/drawings. The University of Utah had specified the electric motor, designed the control system, battery pack and watertight engine bonnet. Thus, the ASU team had yet to see their prototype lower end mated with the power head.

When the student teams met, it was interesting to see how teams interacted. The students were excited to see each other's designs and integrate them together. As the students assembled the complete unit, they were able to explain each other's systems to the outfitters as if they had practiced the routine together. The students were proud of their design and it showed as they explained the functionality and robust features of the newly designed lower end to the customer. Some students covered the design and answered customer questions while other student put the hardware together and made sure the functionality was understood. When the customer had manufacturing questions, the manufacturing students explained how each part was created in detail. The team looked and acted like a team!

The motor adapter plate bolted onto the electric motor without incident and then onto the vertical shaft's keyway adapter. Both school's teams were amazed at the ease of assembly and made several comments on their success in using CADD as a design tool to share information. Having student teams work from institutions in two different states and still have the design fit together well is an important lesson, needed in industry every day. The motor and lower end were placed on the test boat, as shown in Figure 18.

Figure 18. Prototype Testing

After being installed on the river boat, the unit was taken out for testing. Students from both teams left the dock and logged current, voltage, temperature, and vessel velocity. As the throttle was increased, the unit performed well until a point where, along with a clunking noise, thrust was lost. The students backed off the throttle and the noise ceased and thrust was regained. The same thing happened again when the throttle was placed at 100% load. After trouble shooting, it was quickly decided that the torque limiting clutch was disengaging at full throttle. It turned out that the torque limits provided/used during the design phase were low. However, at partial throttle, the lower end sustained the river raft with students on it at 5.6 MPH. Thus, the students felt their prototype testing was a success.

Project Analysis and Assessment

Senior project assessment can be very challenging. The engineering education programs at the College of Technology and Innovation have developed a set of assessment rubrics used to grade project performance. This approach is very useful because of the multidisciplinary student teams and faculty mentors drawn from multiple units. A faculty mentor is often responsible for assessing outcomes and assigning grades for students outside of their home department or program. Furthermore, the capstone course is thought of as the culmination of a student's degree program and is often used to assess their skill set. The rubrics allow faculty and people observing the capstone team's projects and presentations to comment on the level of student attainment. Figure 19 shows an example rubric, one used to assess "design."

Design–An ability to design and develop a system, component, or process to meet desired needs within realistic constraints.

Level 1 Recites the steps and information flow in the engineering design process and uses at least one organizational or technical tool in each step.

Level 2 Given a problem definition, uses a design process and design tools to produce a documented design solution including a prototype, and explains how the design meets the constraints and criteria.

Level 3 Evaluates design process and resulting design quality and suggests improvements.

Level 4 Customizes design process and communication for varying design situations.

Rubric

		Level 1 (Knowing)	Level 2 (Doing)	Level 3 (Assessing)	Level 4 (Innovating)
ABET (d) an ability to apply creativity in the design of systems, components, or processes appropriate to program educational objectives	*Problem Statement*	Identifies the need for a problem statement.	Successfully writes a problem statement.	Evaluates the quality of the problem statement and suggests improvements.	Appropriately adapts their problem statement process to various types of problems.
	Concept Generation, Evaluation, and Selection	Identifies the steps in the concept generation, evaluation, and selection processes.	Successfully does the concept generation, evaluation, and selection processes; documents the design solution.	Evaluates the quality of the concept generation, evaluation, and selection processes and suggests improvements.	Appropriately adapts their concept generation, evaluation, and selection processes.
	Product Realization	Identifies the issues important to product realization.	Creates designs with reasonable consideration of product realization issues; can document and explain their consideration.	Creates a reasonable prototype.	Evaluates the quality of their design prototype relative to a given product realization context.
	Realistic Constraints	Identifies potential constraints on the design process.	Includes realistic constraints through the entire design process	The final design and prototype meets the realistic constraints imposed on the design process.	Appropriately adapts the design process to address constraints.

Figure 19. Design Assessment Rubric

There are different rubrics, e.g., design, communication, technical competence, professionalism, problem solving, and engineering practice. All rubrics are given to the Capstone course faculty mentors and they asked to use the rubrics when possible during the course of the project—whether for individual team members or the team as a whole. The appropriate rubrics are often handed out to other faculty members, project customers, or presentation guests during certain portions of the capstone projects and they are asked to indicate the level of attainment along with any pertinent comments.

Conclusion

This very successful project has become typical of the capstone projects accomplished by multidisciplinary student teams at the College of Technology and Innovation at Arizona State University. The blending of student teams from various programs provides, in a project setting, an educational experience consistent with professional practice. Students are placed into teams where they often do not know the other students with the common link an interest in the project itself. Thus, the students are faced with both a significant technical challenge and with the challenge of becoming part of an effective engineering team. As noted in the paper, the students bonded and rotated leadership roles as needed, taking advantage of the skill sets on the team.

Due the requirement that the team must produce a professional prototype of their design at the end of the second semester, students typically learn a great deal during the project. Computer based designs must become reality and students experience both the frustration and satisfaction of that experience. Such learning prepares them for professional practice in ways that a project requiring only a paper/computer design does not. For instance, students in the lower end design team, while having some background due from their coursework, became much more proficient and confident in their understanding of design and machining. Students designed, programmed, setup, machined, and inspected complex CNC parts. They assembled the parts into a complete machine and successfully tested it. They were able to adapt their engineering skill sets to the project at hand. This was a lifelong-learning experience the student will not soon forget.

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Appendix A

CENTENNIAL INITIATIVE

1916 – 2016

Grand Canyon National Park
Glen Canyon National Recreation Area
www.nps.gov/grca
www.nps.gov/glca

Environmental Leadership

The following centennial proposal is certified as eligible for Centennial Challenge funding consideration in fiscal year 2008. Funding for the Centennial Challenge requires legislation.

Accomplish Alternative Motorboat Propulsion Research

Location: Arizona – Grand Canyon and Page
Partner: Grand Canyon River Outfitters Association, which is comprised of 17 river-running concessioners in Grand Canyon National Park and Glen Canyon National Recreation Area.
Partner Website: www.gcroa.org
Total Cost: $2.8 million
Proposal #137836

Summary: This collaborative effort will develop a new generation of cleaner and quieter boat motors by using alternative fuels, reducing the environmental impacts of boating. This project is a collaborative effort among the two parks' river concessioners and the National Park Service. The ultimate goal is to develop and implement a motorboat propulsion system that offers measurable environmental gains over the conventional four- stroke outboard motors currently used. The hope is to develop a system suitable for use not only in Grand and Glen Canyons, but also in other areas within the National Park System and elsewhere. By working together, the river concessioners hope to capitalize on economies of scale to achieve a greater level of accomplishment in less time.

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Rafting the Colorado River
Grand Canyon National Park