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Design and Implementation of Solar Electric Boats for Cleaner U.S. Waters

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Abstract

Solar electric powered boats may promote zero-emission aquatic transportation and recreation not only for Iowa lakes and rivers, but for all US and world waters. For three years the University of Northern Iowa (UNI) solar electric boat project has recruited students both from electrical and information engineering technology (EIET), and manufacturing technology majors. The problem defined by this paper is (1) developing a novel zero-emission boat, the progress and update on current and the last two years of design, and (2) representing UNI in the annual International Solar Boat World Championship. The race also includes competitions for outstanding workmanship, sportsmanship, outstanding technical report, commercially viable hull design, and outstanding solar system design. In June 2004, the UNI solar electric boat team won four trophies; (1) the most commercially viable hull design, (2) the fastest boat in qualifications, (3) the most improved team from the previous year, and (4) the ninth overall place in world championship. Senior students involved in this project have shown excellent progress by developing their technical and teamwork/social skills as part of the Senior Design I and II courses and successfully completing course requirements.

I. Introduction and Problem Definition

Worldwide, there are more than 20 million pleasure boats and nearly 10 million of them are in the USA. Approximately 236,000 metric tons of hydrocarbons from boats finds it's way into the water every year, equivalent to more than seven times the amount spilled by the Exxon Valdez in Alaska in 1989 [1]. Many boat motors are of the 2-stroke design that burn a mix of oil and gas. These types of motors may be eight times more pollutant than four-stroke motors, since up to 25% of the fuel might be emitted half-burned through the exhaust into the water.

Many people are aware of agricultural pollution in many Midwestern states. Iowa's lakes and rivers are among the most troubled. However, oil and gas leaks, particularly from old boats, illustrate a need for developing eco-friendly boat technologies such as solar powered boats.

For the past three years, the University of Northern Iowa (UNI) has participated in the *Solar Splash* international solar boat competition in Buffalo, New York. Each year has been a learning experience for the teams that were involved. Although touching briefly on the first two years,

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this paper will explore the efforts of the 2004 UNI solar boat team and give a glimpse of what the future holds for the 2005 team.

The team approached the project as a problem solving exercise. As in previous years, the problem could be defined as: "Finding effective and efficient alternatives to internal combustion powered aquatic recreational transportation". There are several reasons beyond the educational experience for undertaking this project:

- Finding an alternative method of getting from point A to point B without emitting roughly 8.6 kg of CO_2 for every gallon of fuel consumed.
- To showcase solar-electric technology in a novel manner.
- Development of a method of recreational transportation that is pollution-free to the streams and lakes that is applicable to our state, country and world.
- To do all of this without taking the fun out of it all.

Because the details of the problem faced by each team differed, the methods pursued would differ each year. The first year team was primarily concerned with making an entry. Subsequent teams built upon the knowledge, experience and challenges encountered by the previous team(s).

The project's main sponsor is Iowa Energy Center (IEC), a non-profit state organization which invests its resources to create a stable energy future for the state of Iowa. Local industries such as Deere and Company, WBM Marine of Waterloo, Square-D Inc, and Rockwell-Collins Inc. also support the project.

This paper describes detailed design and construction of a solar-electric powered boat. This includes sub-systems such as; a fiberglass hull, an electromechanical drive system, pulse-width modulated (PWM) based speed control, and custom made photovoltaic cell modules using commercially available cells. The project has been an excellent asset to the capstone senior design class offered for the EIET and Manufacturing Technology majors at UNI. Students involved in the project have gained knowledge and skills in electrical and mechanical areas. They also improved their social skills since they had to visit many companies and present the project.

II. Solar Splash Competition

2004's Solar Splash was the 11th World Championship on Solar Electric Boat Regatta annual event. It is an international competition open to colleges from all countries, as well as high schools with exceptional technical programs [2]. It is designed to challenge the technical, team-building, interpersonal, communication and strategic skills of the students in a way that is fun and exciting [3-5]. It is not an expensive competition; an entry can be put together for around US$ 5000 including registration, travel, and lodging.

Seven categories contribute to the 1000 possible points used to determine the "Overall World Champion" as follows:

Technical Report	90 points
Visual Display	40 points
Workmanship	20 points

Qualifying Round	100 points
Solar Slalom	100 points
Sprint	250 points
Endurance Run	400 points
Total:	1000 points

In the overall competitions, UNI's record is 17th in 2002, 17th in 2003, and 9th in 2004. In 2004, UNI also brought home honors for "Most Improved Team" and "Most Commercially Viable Hull". Trophies are also awarded for several of the point areas and many design and workmanship type categories, as well as Sportsmanship, Perseverance, Rookie Team performances, and "Hottest Looking Boat".

To assure safety, fairness, smooth running events and also give rookie teams a break – rules do of course, exist. Regulations for fairness include rules pertaining to the seaworthiness of craft, voltage limits, automatic bilge pump required, dead-man switch, wiring practices, floatation devices, craft floatation, etc. For fairness; ballast, power limits (solar, battery size, type), power source, permissible storage, nightly impounding, penalties and other things are spelled out. Administrative items include rules for configuration, eligibility, course layouts, how the event is run, point calculation, physical size, materials, and construction practices. Also worth noting is the "Solar Express Class" which gives rookie teams a way to get a quick start and eliminate some time consuming tasks. Teams can be classified as such for two years.

III. UNI's Department of Industrial Technology and EIET Program

Industrial Technology is a department within the College of Natural Sciences at the University of Northern Iowa. There are six undergraduate programs offered through the department and listed as follows: Construction Management, Electrical and Information Engineering Technology, Technology Management, Graphics Communications, Manufacturing Technology, and Technology Education and Training. Graduate programs are Master of Arts Degree in Technology and Doctor in Industrial Technology.

The introduction of renewable energy applications to electrical engineering technology curriculum at the University of Northern Iowa (UNI) has positively impacted students, faculty, and the University community. It has also promoted the feasibility study, and adoption of more eco-friendly energy technologies.

The EIET Program is a four-year undergraduate program leading to a Bachelor of Science (BS) Degree in Electrical and Information Engineering Technology area. The major prepares students for *application oriented engineering technology careers* in conventional and renewable electrical power, analog/digital electronics, microcomputer, telecommunications, and networking areas. There are also elements of mechanical, hydraulic, and pneumatic system controls as part of the curriculum. The EIET program was updated from an Electro-Mechanical Systems Program. It is also the first and only program in the state of Iowa that grants its students a BS in electrical engineering technology after the completion of a four-year course of studies.

The Manufacturing Technology program is a four-year undergraduate program leading to a BS degree. The program has three emphasis areas: Automation & Production, Design, and Metal Casting. The major is designed to provide relevant and contemporary learning experiences to prepare students to manage technical, managerial or service careers in manufacturing or related industries. The EIET and Manufacturing Technology programs have 2+2 articulation agreements with Iowa community colleges.

IV. Project Methodology and Design/Development of the UNI Solar Boat

Figure 1 illustrates initial ProE design of solar-electric boat hull and placement of PV modules.

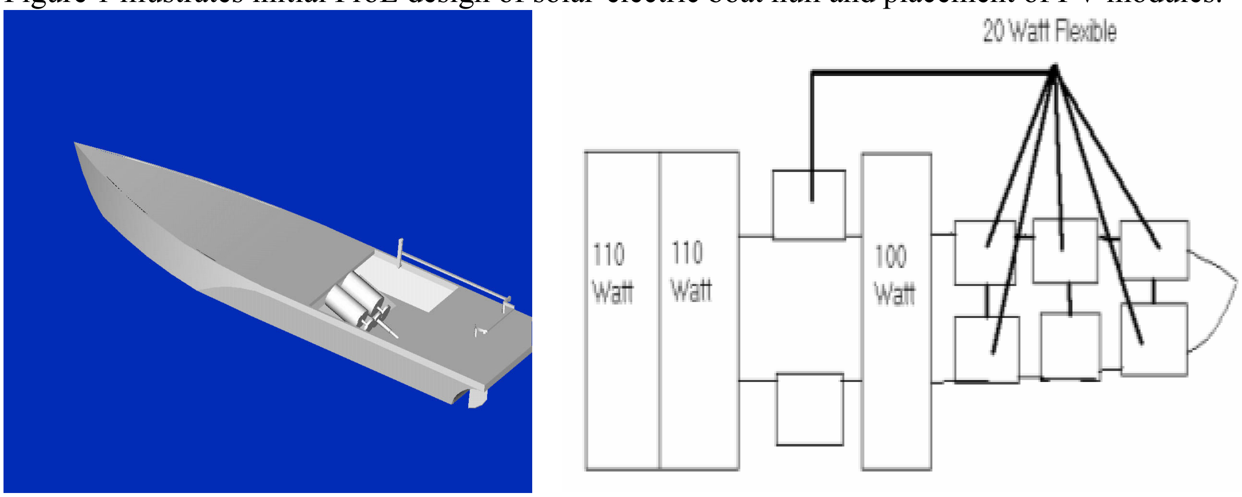

Figure 1. Initial ProE Design of solar-electric boat hull and placement of PV modules.

The following pictures show fiber glass boat hull manufacturing by 2002 UNI Solar Boat Team.

Figure 2. Fiber-glass Hull Manufacturing

The selection of the proper motor is quite possibly the single-most important aspect toward the creation of the UNI solar boat. Due to the competition's format, the 2002 UNI team decided to use two different motors. The same motor was used for the sprint and slalom events, but a much smaller motor had to be used for the endurance race. Motor selection was determined by researching the performance curves of each motor of initial interest. The specific performance curves that were focused upon were those that dealt with speed, torque, current draw, voltage, and overall power usage as shown in Figure 3.

The sprint and slalom races require a motor that has a good torque versus speed performance curve. The motor that 2002 team chose is the same motor that is used for starting large John Deere tractors. This motor is a product of the Nippodenso Corporation. The Nippodenso starting motor is a DC motor that is rated for 7.8 kW at 24 V.

The endurance race requires an entirely different motor setup. The team decided to use a 1/3 horsepower General Electric DC permanent magnet motor. To run a motor under its full potential is highly inefficient, so our team had intentionally undersized our motor to utilize all the power generated by the solar panels. The endurance motor was rated for 12 V and 35 A of current while having a speed of 3050 rpm. Some electrical components were subjected to a cryogenic treatment which involves slowly freezing the component to a temperature of –320 ° F and then slowly bringing it back up to room temperature [6]. This process has proven results in improving the efficiency and power output of the electrical motors. The cryogenic process aligns the poles of the copper molecules and improves the electron flow through the battery cables, armature, and motor coils. Comparing power before and after this treatment on a dynamometer, the treated motors had a power gain of 10-15%.

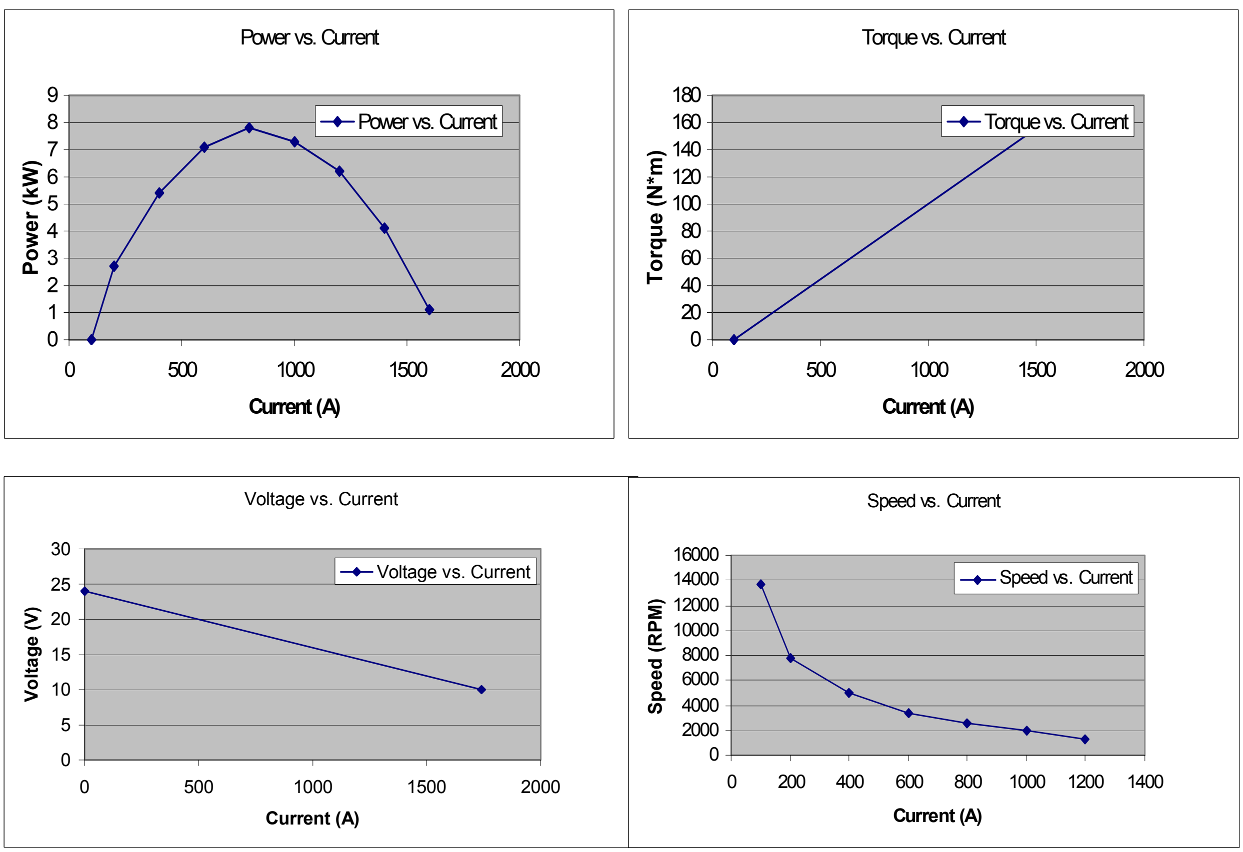

Figure 3. Electric Power, Torque, Voltage, Current, and Speed Characteristics for the motor

Testing

While building the boat, numerous calculations were performed to determine how it would sit in the water, the weight displacement that would be needed, and the amount of buoyancy the boat would provide. Size, shape, and the amount of flotation material used to form the boat's top piece were all taken into consideration. Nevertheless, the boat had never been in the water even prior to weighting it down with hundreds of pounds of equipment and body weight. Just prior to backing it down the ramp, masking tape was used to create a grid on the side of the boat so that visual record of how the boat rode and planed out in the water could be taken. The initial test run was successful as seen in Figure 4.

A number of tests uncovered the following problems:

- The front of the boat was reluctant to plane out of the water.
- The boat had taken on more water through splashing than the team felt comfortable with.
- Motor overheating.

(a) (b)

Figure 4. Motor frame designed and built (a), and test-drive (b).

- Loose wire on solenoid circuit.
- Power density limits were exceeded in the batteries.
- The boat's weight distribution was not optimized for bringing the boat into cruising plane.
- Fabricating new mounting brackets for battery.
- Building a water tight box around the motor that would hold dry ice.
- The motor was turning too slow at load (1500 rpm from 9440 at no load) contributing to overheating.
- Propeller diameter was too large for the torque delivered by the motor.
- Propeller had too much pitch and was reduced from a 13 to a 10 pitch.

The modifications to solve the aforementioned problems not only improved the initial jump off the line, but the boat also picked up a lot of top end speed. Finally, a video tape of the test trials was made to see exactly where the boat traveled in the water after redistributing our weight and making the necessary propeller changes. Finally, the testing, modifications, and time invested will ultimately lead to the creation of a competitive boat that would represent UNI [7].

For 2004, the outcome of the previous year's competition was analyzed by the team. Three major challenges for improvement were identified:

- The boat needed to have less drag in the water.
- The boat needed an improved drive system.
- More pre-race testing was needed.

To have less drag in the water, two approaches were explored; the first was to lighten the boat itself, and the other was to improve streamlining. Several opportunities for light weighting the craft were found.

Drive system improvements were divided into two parts, mechanical and electrical. Possibilities for mechanical improvements included; better propeller shaft alignment, a new motor mount and using a new propeller shaft with more efficient sealed bearings.

The team planned activities through a Gantt chart schedule that required testing to start several months in advance of the competition. This was to assure adequate time to find system weaknesses and address them with time to spare *prior* to the June event.

Details for Meeting these Challenges

The lighter the boat and its' contents, the less water it displaces. This displaced water equates to drag in moving the boat through the water. Therefore, it follows that a lighter boat has less drag. The motor mount, steering bracket and control panel were rebuilt out of aluminum. This saved several kilograms. The greatest weight reduction was realized in rebuilding the solar arrays. The new arrays were hand-built from individual cells mounted on lightweight foam. The 2003 array consisted of four panels weighing nearly 13.6kg (30 lbs) each. The entire 2004 array weighs just slightly over 4.5kg (10 lbs). This reduced the weight of the craft by nearly 49.9kg (110 lbs). The majority of the weight in the arrays now comes from the cells themselves instead of their mount. Four panels of (36) 3.3W cells arranged in a 4 x 9 pattern make up the array. This gives a nominal output of 475 W, which is just under the 480 W (at one sun) limit set forth in the rules. Testing verified that the array was acceptable.

The shape of the hull itself was already established and was not within the scope of what the team wanted to change for 2004. There were however, a couple of improvements to be made beyond the hull itself – the stabilizer bumpers were removed, and the rusty steel propeller shaft was replaced with a stainless steel version. These may seem small, but every improvement helps. During testing, it was determined that moving the batteries far forward allowed for more efficient plane level. This worked to reduce hydrodynamic drag as well. The drive system was a major focus for the 2004 team. There were mechanical and electrical aspects to the overall effort. By the nature of the project, they intertwine with each other. The term determined that the previous year's motor was unacceptable. An under drive pulley system was created that would reduce the speed of the propeller but significantly increase the torque output at the propeller. This test setup was modeled in Pro Engineer and can be seen in Figure 5.

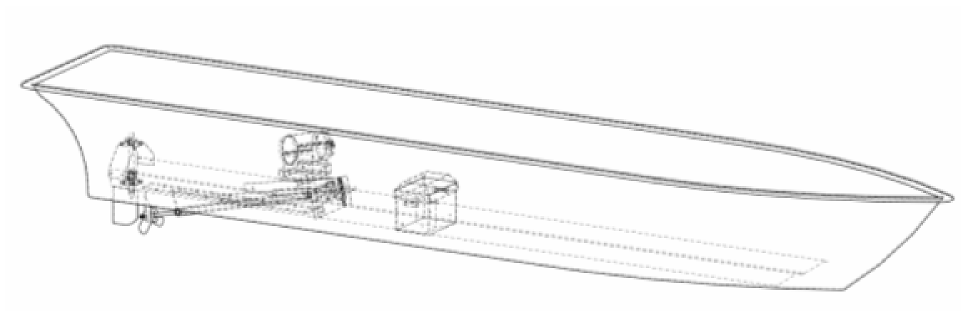

Figure 5. Drawing of eBoat with experimental pulley drive system

The nylon bearings that the shaft spins in have also been replaced with new sealed stainless-steel bearings. This change provided for less friction loss compared to the 2003 boat. A propeller was chosen to provide maximum thrust in the largest diameter that will fit under the boat without interfering with the bottom of the boat or the rudder. The propeller is a three-blade type with a 10.5" diameter and a pitch of 13" per revolution. Figure 6 shows the drive train system with the new shaft, new bearings, and propeller [8].

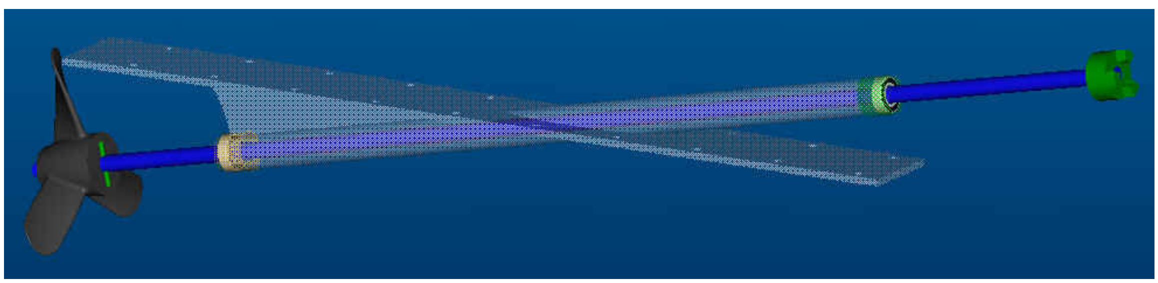

Figure 6. Three -dimensional model of new output shaft

It was determined that the speed controller was still under rated and the boat was quite slow. New components would be needed to achieve the team's goals. The team wanted to create a boat that draws attention and sparks interest for further consumer use through the team's innovations of competitiveness in the Solar Splash competition. The team decided to purchase a 15 peak HP Etek motor and an Alltrax 650 A PWM programmable speed controller. The motor was selected for its great efficiency, low weight (21 lbs), high power rating (15 HP peak, and 6 HP continuous) and good price. It is also capable of drawing 330 A for up to 1 minute without damage. One major benefit to this motor over the motors used in 2003 is its' light weight. Weighing in at 20.8 lbs, this motor is 20 lbs lighter than the 4 HP motor used previously. Another advantage is the higher speed and torque output of this motor. It is rated at 72 rpm/V, resulting in a propeller speed of 2600 rpm at 36 V. Torque output of this motor is rated at 1.14 in*lbs /A resulting in 380 in*lbs of torque put to the water. This motor is also efficient in its use of energy due to the neodymium permanent magnets and the copper bus bars. The permanent magnets allow the motor to create its own electric field in the stator. The copper bus bars give the motor an extremely low internal resistance. These key advantages greatly reduced losses and saved more power for use in propelling the boat. The Alltrax AXE-4865 speed controller was selected for its current handling ability, efficiency and programmability. This controller operates between 24-48 V and is rated to handle 650 A for up to two minutes. The controllers' five minute rating is 400 A and its one-hour rating is 250 A. The controller consumes less than 0.08 V per 100 A allowing for extremely efficient operation. While the team could have purchased a controller that was more closely matched to the current rating of our motor they choose the 650 A model to accommodate any growth in output by future teams. The programmability of this controller has proven to be useful, as it will protect the motor, batteries and wires from over-current damage if properly programmed. Since our motor is capable of handling 330 A for up to two minutes, the controller was set to limit current to approximately 400 A.

Energy storage and power conductors changed for 2004 as well. For the sprint and solar slalom events the boat uses three 17.44 kg (38.4 lb) Optima 34M deep-cycle 50 Ah marine batteries. For the endurance event the configuration changes, the boat uses two 19.73 kg (43.5 lb) Optima D34M batteries with a 55 Ah rating and one 27.1 kg (59.8 lb) Optima D31M deep-cycle battery with an 80 Ah rating. The Optima D31M battery is only being used in the endurance because the extra capacity is not needed in the other two events. Also, the Optima 34M and D34M batteries are at least 16 lbs lighter than the D31M battery for more speed due to the reduced weight.

Cost Analysis

The following table illustrates a cost analysis of 2003 boat development. The Iowa Energy Center (IEC) provided a funding of $2,000 per year for the project from 2002 through 2004. The IEC has also granted the project $5,000 per year from 2005 through 2007.

Item	Price
Boat Hull Material and Manufacturing	$650
Solar Panels (4 Solid, 8 Semi-flexible)	$2,480
Deep Cycle Marine Batteries & Cables	$350
Propeller, Gear Box, Shaft, Seals, Bolts,	$520
Framing Material RS-232 to DC Motors	$1240
(4 Hp, ½ HP, 11 HP JD Starter Motor)	
Bilge Pump, Kill Switch, Drive Shaft PV	$180
Mountings, Steering Mechanism	$200
Travel Expenses for Solar Boat Team	$1150
Race Fees	$250
Miscellaneous	$600
Total	$7,620

Were the Challenges Met?

The outcomes were dramatic for each of the three challenges. The reduced drag was evident right away in testing. It became more apparent throughout testing and in competition that the efforts were going to pay off. The drive system held up as expected. The performance far exceeded that of the previous drive systems. The controller was able to withstand all loads drawn through it. The motor provided consistent power throughout the event. Testing proved valuable as well. The team was able to find out how far and how long the motor/controller combination could be pushed. It was beneficial to “know” the batteries and what could be expected of them as well. This continuous project has also been a useful asset for future an ABET accreditation application for the program [9].

UNI Placement in events

As a result of the team’s efforts, UNI’s placement in the various events was improved over the prior two attempts. Overall, the team’s standing was improved from 17th to 9th. The team also brought home honors for “Most Improved Team”, and “Most Commercially Viable Hull”.

In the events that make up the competition, UNI's placement is as follows:

Qualifying Event	100/100 points	1st place
Solar Slalom	96.83/100 points	3rd place
Solar Endurance	167.40/400 points	15th place
300 Meter Sprint	184.89/250 points	7th place
Technical Report	70/90 points	5th place (3 way tie)
Visual Display	28/40 points	6th place
Workmanship	10/20 points	14th place (2 way tie)

V. Goals for the 2005 Solar Splash

The efforts by the 2005 UNI Solar Splash team are currently well underway. The team has identified several new goals to further improve the team's competitive position:

Goal 1. New Hull: It is felt that although very maneuverable, the shape of the current hull requires the drive system to push through the water more than glide through it. A new fiberglass hull to replace the current one is planned.

Goal 2. New Drive System(s): Using what was learned in 2004 and taking it further.

Goal 3. Semi-flexible PV Cell on the Hull: This will eliminate the need for a separate panel. The cells will be mounted directly to the hull. This will require that they be semi-flexible in order to conform to the shape of the hull.

Goal 4. Use of Two Separate Motors: The Etek motor was good in the sprints, but was too large for endurance. The battery was drained very quickly and did not allow for a long, sustained effort. A smaller motor is more closely matched to the requirements of that event. The old saying "slow and steady wins the race" truly applies here. Many of the higher place finishers were well within striking range in 2004. If the endurance event were in line with UNI's performance in other events, they could have placed much higher.

Goal 5. Improved Charge Controllers: A new charge controller is needed that more appropriately addresses the charging conditions.

VI. Instructional Practice for Institutions Planning to Develop Solar Electric Boat Design

The solar electric boat development project at UNI has been established to promote interest in Science, Engineering/Technology, Education, and social interactive skills. Annual funding through the state of Iowa has allowed the project to continue successfully since 2000. The project has provided students and faculty advisor an opportunity to apply theory to a practical project in a team environment. It has also served as an opportunity for students to compete and showcase their accomplishments in an international competition where a number of engineering and technology colleges are involved.

In the very beginning of the project, students are required to research and understand hydrodynamics fundamentals such as basic floating, buoyancy, and Archimide's Principle. Students on the project team are required to develop small prototype modules to test the aforementioned fundamentals. They are then asked to add small prototype equipment such as small sized solar cells, dc motor(s), frames, fans, simple gear boxes for coupling, battery storage, and if possible remote controls and demonstrate their own models in a water tank. This practice has provided students the confidence needed for the actual solar boat development.

ProE™ has been a very flexible CAD design tool for solar boat hull development. Most of the manufacturing technology and EIET majors have knowledge and skills on the ProE™ software and therefore the solar boat development has been a good use of their expertise. Due to delays in the purchasing process, students order the material and equipment before finals in fall semester. This avoids lost time while the orders are processed through department, college, and central administration in the university. Students prepare two major technical reports. The first one is due at the end of the fall semester showing objectives, and details of the design. The second one is the revised version, showing all activities (such as testing, revisions, retesting and strategic planning) that have taken place since the initial submission. These reports are critical to the learning process, in that they force the team members to critically think through every step and why those steps were taken. Additionally, there is the experience of writing these papers, simulating on-the-job communications that they will be required to perform on a daily basis upon graduation.

In order to construct the actual boat, team members must utilize various skills gained through classroom instruction. These skills include; design, brainstorming, application of supporting sciences, fabrication, project management, wiring, testing, instrumentation, planning for efficiency, and troubleshooting. This allows them to experience within a single project many of concepts they have learned in their underground education.

Building a solar boat cannot be a specific course in the Engineering Technology area where a number of major core, technical electives, and liberal art courses have already limited maximum hours offered. However, it draws upon nearly all previous courses students may have had. The faculty advisor initially provides objectives, fundamentals, technical challenges, and disaster avoidance. He/she also explains rules and regulations on design and implementation. Then the student role as a team begins. After becoming well-grounded with the fundamentals, goals, and rules, the project leadership is slowly transferred to the student team leader and members. The weekly meetings with team and the advisor keep the project on schedule. For the first time ever a graphics communications major has joined the team to maintain the project website and enhance public relations for promoting the project in the community.

VII. Conclusions

Design and construction of a solar-electric powered boat and racing in an international competition to promote clean boating technologies have been an excellent learning experience for senior students in the Electrical and Information Engineering Technology and Manufacturing Technology majors at UNI. In addition to bringing classroom theoretical knowledge to life in an applied project, students have learned how to work collaboratively in teams to solve problems similar to those that they may encounter in their careers after graduation. The success that the senior design course has enjoyed through the complexity of the project undertaken by the students is an excellent indicator of the validity of the courses in the curriculum. Similarly, all engineering and engineering technology programs are strongly encouraged to incorporate renewable energy based senior projects into their curriculum to promote eco-friendly energy technologies for a brighter future for our later generations. Many interested local and regional, private or public elementary, junior high, and high school students and teachers have visited this project in the last three years. There has been strong media coverage showing the project to the public. This has also increased awareness of Engineering and Technology among young Iowans whose families are mostly dealing with agriculture. There is no doubt that student recruitment has already been impacted positively as well. The EIET program has an increase of enrollment of 25% from 2003 to 2004.

UNI prepared for and took part in the Solar Splash competition. Through planning, strategizing, and faithfully executing the plan the team improved UNI's overall placement, and placement in the separate events over any other year's effort. The team has identified several new targets for improvement in the 2005 event. It is hoped that the UNI entry will have a positive impact on aquatic recreational transportation. The team desires that this be looked upon as a preview of what is yet to come in this area. All goals were met for the 2004 project and event.

Solar-electric boating does present a viable, environmentally friendly alternative to the status quo of the current state of recreational boating. There was no CO_2 emitted by any of the craft competing during the event, an exciting demonstration of solar-electric technology was presented by all teams, the students had a valuable learning experience and they had fun doing it.

VIII. Acknowledgements

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Biographies

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Michael Hay and is a graduate student at the University of Northern Iowa pursuing his masters of art degree. Mr. Hay holds a BT in Industrial Technology/Mechanical Design from the University of Northern Iowa. Mr. Hay has over 25 years of experience in various Engineering positions. His graduate research is in planning and implementing small-scale wind-electric systems. He has worked on several other renewable energy and electric vehicle projects as well. Mr. Hay has been a member of Epsilon-Pi-Tau since 1979. Mr. Hay has received State of Iowa governor's volunteer award through the Department of Natural Resources (DNR) in 2001. Mr. Hay has been co-inventor of three US patents in product design.