2006-1794: UNDERGRADUATE RESEARCH AND CREATIVE ACTIVITY AT MIDDLE TENNESSEE STATE UNIVERSITY

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Undergraduate Research and Creative Activity at Middle Tennessee State University

Introduction

This paper discusses undergraduate research and creative activity at Middle Tennessee State University as implemented as a capstone course and design project. Four seniors from the electro-mechanical and mechanical disciplines applied and were partially funded to do undergraduate research. Their project was to build a boat to compete in the national Solar Splash competition. "Solar Splash is the World Championship of Solar/Electric boating. It is an international intercollegiate competition that takes place over five days"[1]. For their work, the seniors received credit for the capstone senior project class. As part of the work, the seniors led a team of freshman and sophomores. The benefit to this relationship: the seniors exercise their creativity and classroom knowledge while gaining valuable project management and decision making experience. The freshmen and sophomores also benefit as they work alongside the seniors; they get hands on experience as the engineering principles that they are being introduced to get put in to practice. When they become seniors themselves, they will be able to put all of that experience and classroom knowledge to build a new and improved solar boat, and lead a fresh batch of young engineering minds.

MTSU's Undergraduate Research Center promotes and champions change that institutionalizes a culture of inquiry and scholarship for all students and will coordinate the integration of research-based learning in undergraduate education, from the introductory experiences to the senior capstone experiences[2]. This culture of inquiry was evident during the design and construction of MTSU's solar boat. The areas of research undertaken by the student team included: propeller design, hull design, drive train design, and designing the solar array. Hull weight, displacement of water, and aerodynamics all play critical roles in the success of the boat design. The boat must also be strong; this leads to researching suitable construction methods and materials. The student team must make decisions based on their research as to the most efficient design. This frequently resulted in the crafting of scaled models, computer modeling, and subsequent testing.

This project, with all its possible variables in design, placed a special emphasis on learning. It also brought out a competitive pride in the students to craft a solar boat capable of winning the Solar Splash competition.

Regulations

Regulations are present that affect every aspect of the chosen design. Examples of regulations include buoyancy of craft, solar panel attachment, and drive train fastening. These along with all other regulations are available at www.solarsplash.com. The event consists of three major competitions. The endurance, sprint, and slalom make up the total event. The major portion of the competition is the endurance event. The watercraft must have excellent power management, an efficient hull design, and the appropriate drive train and propeller. These criteria must be met to have a successful craft. The power management consists of the proper batteries, motor(s), and electrical system. Also an extremely efficient solar array is necessary to prolong the crafts endurance. All engineering and design aspects will be tested to their limits. The sprint will test the boat's overall hull design. The idea of the sprint is very similar to that of a drag race in that you exert as much power as possible over a short distance. Hull weight, displacement of water, and aerodynamics play the most critical roles. The slalom is an overall test of the boats maneuverability, handling, and structural rigidity. A craft which is not structurally sound will fail in this event. Each area of the competition will be weighted and scored. The team with the most points will be the overall winner. Table 1 is a break down of the scoring for the event[3].

Technical Report	90
Visual Presentation	40
Qualifying	100
Workmanship	20
Slalom	100
Sprint	250
Endurance	400
Total Points	1000

Table 1 Solar Splash Scoring

Hull Construction

The hull design of the boat is one of the most critical aspects of this competition. Most of the time spent on this project would revolve around the design of the hull. Several of the team members meet weekly for a period of three months to research and discuss different aspects of the hull design. First, the craft must meet the criteria for the regulations. By familiarizing ourselves with the regulations the team could start setting guidelines for the design. Some of the most significant regulations concerned with the design at this point were the following:

Technical Specifications	(Size limitations)
Materials	Teams are encouraged to be creative in the selection of materials. The only restrictions are 1) flexible materials are not allowed to create a sail, 2) any materials that would pollute the water are not allowed.
Visibility	The skipper must have unobstructed vision forward and at least 100° to either side.
Stability	Due to time constraints, it may be necessary to conduct events in less then ideal conditions. Since safety is vital, the stability of the craft will be tested by placing 10 kg at the sheer line (outer edge at beam) with the skipper stationary in the normal operating position. Craft must not heel more than 15°. Skipper must remain centered with hands/feet in normal position.
Skipper Cockpit	The skipper's cockpit must provide for the skipper's unassisted exit within 5 seconds in case of emergency.

Solar Panels	Each panel, with or without a frame, must be attached with a mechanical fastening to the hull. The design should take into account the possibility of gusty winds during the events. In addition, a lanyard must be attached from each solar panel to a secure member of the hull or a frame that attaches to the hull. The lanyard must be strong enough that it will not break if the panel should go into the water while the boat is moving.
Buoyancy of Craft	Sufficient flotation must be provided on board so that the craft cannot sink. A 20% safety factor must be included in the calculations.
Towing	A fitting for emergency towing must be attached at the bow. The hole diameter must be at least 14 mm (.56 in).

Table 2 Solar Splash Regulations Regarding Hull Design

With all of the previous regulations in mind, concepts of the hull began to arise. The hull needed to be as light as possible. The mass of the hull could be a big contribution to the overall weight of the craft. The more the hull weighs, the more force is required to move the craft forward. The more force applied translates into a greater use of electrical power, and part of the competition will require our craft to be efficient.

While contemplating the efficiency of the craft it was determined that fluid dynamics would be another important factor that will greatly influence efficiency of the craft. A boat interacts with two fluids: air and water. Ideally the craft should come out of the water and into the air. The air will exert less pressure on the hull when it is moving forward, thus the craft will be operate more efficiently. To get a better understanding of how fluid dynamics plays an important role in the design, the effects of pressure must be examined.

Pressure, exerted by a gas or liquid, is the microscopic collisions between atoms or molecules in the gas or liquid and the surface experiencing the pressure force. The motion of the particles is random. The change in motion of the particles during a collision with the surface corresponds to a change in momentum of the particles, which results from a force exerted by the surface on the particles. Newton's 3rd law describes that there must be a corresponding force of equal magnitude and opposite direction exerted by the particles on the surface[4]. The corresponding force is represented by the force supplied by the drive train and the power system. So by understanding Newton's 3rd law and knowing how pressure plays in fluid dynamics, the two fluids we are working with can be evaluated. The density of water is 995.7kg/m^3 and the density of air is 1.165kg/m^3. By comparing the two densities water is 885 times denser than air. Since the number of particles corresponds to density, water will exert many times more force against the surface of the hull than air. The design challenge for the team was clear: design a hull that will displace the less dense air instead of displacing the denser water.

The hull is more efficient out of the water, and the slower the speed that the hull comes on to plane the less energy we will consume. Picking a design that supports these goals was the next problem. There are several boat designs capable of achieving the goal of traveling through the air either by skimming the top of the water or using air to generate lift.

After determining what type of hull design was needed, the team examined different types of hulls. Although semi-displacement hulls seemed to be the most common for the Solar Splash competition, it was decided to look at as many different designs as possible. The designs that were considered were the following: the V-hull, the catamaran hull, and different variations of air-lift hulls also known as hydroplanes. The V-hull design seemed to have many benefits associated with it. The V-hull typically has good maneuverability. The solar array can easily be adapted to fit on top of it. The steering will be responsive due to the flow of water coming to a point in the rear. The V-hull still has a disadvantage; it requires a great deal of energy for the hull to plane. The next type of hull that we considered was the catamaran, which is sometimes called a double v-hull or tunnel hull. The hull consists of two v-hulls which are connected with a tunnel. When the boat is in motion air is forced through the tunnel, which creates lift. Although total plane is not achieved it can be more efficient than a V-hull. The next designs our team began researching are based on the air-lift. These different hulls are known as traditional 3 point hydroplane, cab over hydroplane, tunnel hull, reverse 3 point hydroplane, and hydroplane outrigger. The hydroplane outrigger was one of the first designs considered. After the information was gathered for the different types of hulls, the choice came down to a conventional 3-point hydroplane, Figure 1, and an outrigger design, Figure 2.

In choosing our hull design the team looked at many factors. The factors focused on consisted of the regulations listed in the previous section, as well as placement of the solar panels, ease of construction, location and description of the cockpit, location of the drive train etc. One of the very first concepts can be seen in Figure 3. Still the main factor associated with any design was to keep the weight at a minimum. After extensive researching it was decided to go with a 3 point hydroplane.

Another design aspect of the hull was the method of construction. Traditional boat building methods use wood as frame support and then the wood is covered with fiberglass. In the design process the team looked at building a mold to construct our hull. Having a mold would eliminate the heavy wood frame. Another benefit of constructing a mold would be that it could be used again fairly easy.

Next, the team researched the different types of composite that we could construct the mold-less design. Options included several types of fiberglass composites as well as different types of graphite and graphite blended with other materials. Since weight and strength were equally important, graphite composite was chosen.

At this point the hull design was chosen and the construction methods as well as materials have been selected. The details of the items chosen are described in the following section.

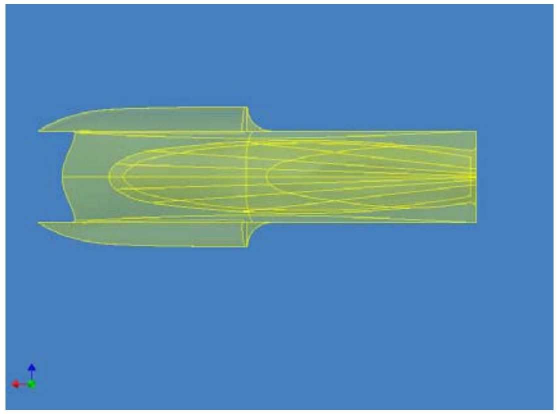

Figure 1 Top view of a conventional 3 point hydroplane.

Figure 2 Model of a Hydroplane outrigger.

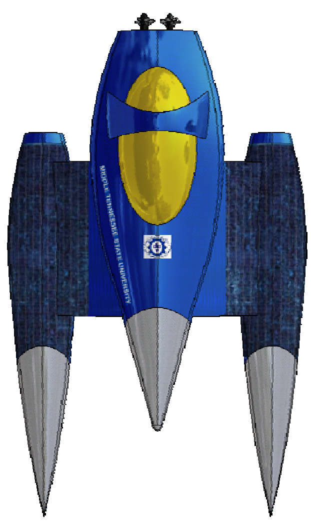

Figure 3 First concept

The hull of the 3 point hydroplane consists of a flat bottom and two sponsons. Air is forced between the sponsons, which creates lift for the rest of the hull. When the craft reaches plane it rides on 3 points. The propeller and the rear of each sponson are the only parts in contact with the water. With this design there is almost no resistance from the water. The only disadvantage is the power required to plane out the craft. However once the boat reaches plane the amount of power needed to keep it planed is extremely low.

Although we have selected a hull design, we still need to solve several unknowns. The first unknown concerns the dimensions of the craft, such as the length of the craft, the depth and how long the sponsons should be. Determining the surface area of the top of the craft was done by the size in which solar cells could be arranged to supply the 480 watts of power. A second factor involved the placement of the sponsons and the angles that make up the sponsons. Thanks to AeroMarineResearch.com we found the range of the different angles that composed the sponsons. We ended up using the averages of those angles. Jim Russell of AeroMarineResearch.com, and author of several boat design books and tunnel hull software, informed us that the angles were specified by the designer based on preference. Since the design is based on preference only, we felt it would be acceptable to use the averages.

After all research was completed on the construction method of the hull and the materials that we would fabricate it out of, we decided to use a mold-less design. With this design we were able to construct a one part craft without the use of wood, metal or other materials that can add excessive weight.

The material we chose to construct the hull was a Carbon Fiber-Kevlar Hybrid from Fiber Glast. This material consists of strands of carbon fiber and Kevlar woven in opposing directions. Each individual strand of carbon has three thousand fibers, and each strand of Kevlar has 1500 fibers. This material was chose due to its light weight and its high strength. The carbon alone has excellent rigidity properties but poor tensile strength. Kevlar on the other hand is just the opposite. By combining the two materials both desirable specifications are met.

We chose to use two inch extruded polystyrene for construction of the hull. The foam is lightweight and can be easily shaped. The hull was drawn in Solid Works and then we printed out the outline of the hull. The next step was to glue together the extruded polystyrene foam sheets. Then the outline was attached to the side of the foam and cut out with the use of a hotwire. Once the sections were cut they were glued together and then the finishing sanding was done. The foam was coated with a layer of latex paint was made before applying the fabric. This was done so that the foam would not soak up as much resin, which would add undesirable weight. Once the hull was painted the fabric was attached to the hull with epoxy resin and hardener. Each layer of fabric was oriented in a different direction to increase its strength. We used three layers of fabric on the bottom of the boat and four on the sponsons. We felt that this was necessary since this area would be under the most stress. As for the top we used two layers, since its main purpose was for aerodynamics.

A layer of resin was painted, starting with the latex-coated foam. Then the first layer of fabric was applied. More resin was applied, and then all subsequent steps were repeated for the layers. Once a layer was attached, plastic spreaders were used to squeegee off the excess resin and apply it to other areas. With this method the team was able to stop any excessive build up of resin, thus eliminating extra weight. Once all layers were applied it was allowed to sit overnight. When the material was fully cured, overlapping excess material was ground off. The next step was to address the seams were the layers mated. This was done by grinding down the material and applying additional strips of fiber along the seams. When all of this was completed the hull finished. After the hull was completed the team proceeded to carve out the cockpit and the rear deck from the solid body. Most of the foam was removed, except for the sponsons and areas where we needed cross sectional support. This was done to keep the craft as light as possible. We applied more fabric on the foam inside the rear of the boat to give it extra strength. These additional support areas were also used to mount the electronics and other necessary items. After the reinforcements were made, the cockpit was molded to the desired shape and more carbon fiber was added to give it a clean look. At this point the craft was solid, rigid, and structurally sound.

The general descriptions of the hull design, the construction method, and the construction materials have been specified thus far. The next step for this design was to further our knowledge of this design by determining the rest of the factors that can help or hurt the performance of the craft. Once all remaining factors had been identified, some testing needed to be performed and the results determined the estimated outcome of the design.

Design of experiments

While the team was researching all of the different configurations of this type of craft, it was noted rather early that there was just not a great deal information available for 3 point hydroplane designs, and there were still some unsolved factors. To determine how these factors would affect the design, testing would have to be done. Initially the team considered a water flow tank to test a scaled model. However, since the design was based on air lifting the hull, testing the design in a flow of water would not give the answers sought. The team did however determine the factors that needed to be answered. These factors are the following:

1. Attack angle of the hull
2. The location of center of gravity
3. The angle of the propeller
4. The effect of weight
5. Effect of using an inboard or outboard drive train
6. If channeling the air with rails will offer any benefit

Several of the team members began looking for an answer for our testing purposes. Through research, discussing with several faculty members in the Engineering Technology Department and the Aerospace Department, came up with a plan to test our model. First we needed a model. The team drew a model in Inventor 8 and built a model out of Styrofoam using a Fadal VMC3016. With the testing completed, the main factors that had to be improved were the weight and the angle of the hull. The team knew that the lighter the hull, the better the results, but after the DOE we knew by how much. The angle of the hull was critical. If the team had not tested the design, the angle of attack initially chosen would have been devastating. Now that all of the unknowns were solved, the craft was ready to be built.

The result was an efficient streamlined hull with an understanding that weight must be monitored in order to be the most efficient. Figures 4 and 5 show a computer model of the design concept.

Figure 5 shows the Styrofoam plug based on the computer model. Figure 6 shows the carbon fiber material being applied to the plug.

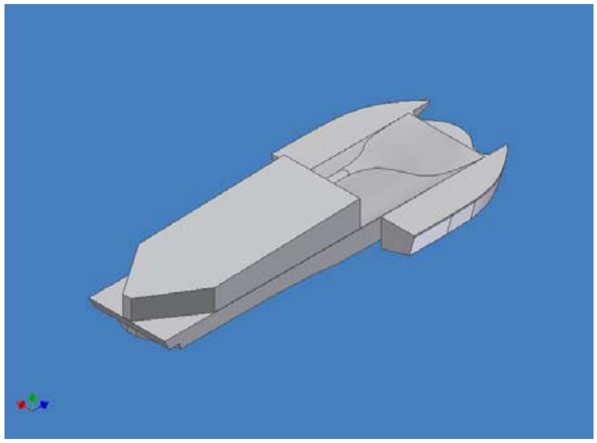

Figure 4 Computer model of design

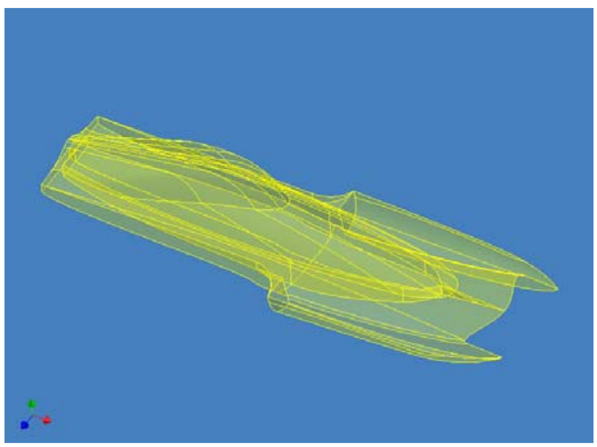

Figure 5 Refined computer model

Figure 6 Styrofoam plug

Figure 7 Carbon fiber body work

The portion of the competition valued most heavily is the endurance event. This event is weighed at 40 percent of the total competition points. For this reason, a design specialized for the endurance event will be given the most consideration. The focus of the design will be optimizing the power system and drive train for energy efficiency. Because the hull design was chosen to be a 3-point hydroplane, the craft will need to operate at a minimum speed which was determined in the DOE. This method of operation will result in a faster rate of energy consumption, but, as stated previously, the energy will be used more efficiently.

Drive train

The two main considerations for drive configurations are inboard motor(s) with shaft driven propeller, or outboard motor(s) and a propeller driven through a lower unit. The main advantage of the inboard system is the ability to relocate the weight of the motors to help balance the weight of the entire craft. The complication that comes with mounting the motors inside the hull is driving the propeller with a shaft that goes through the hull. This requires the holes made for the propeller shaft to be water tight. Because the propeller is mounted in a stationary position, steering would have to be accomplished with a rudder system. For an outboard, the advantage is having all of the drive components combined in one unit. The unit is mounted to the transom on the rear of the hull. The steering of the craft is achieved by pivoting the outboard, and therefore the propeller, to the left and right. This allows for a simpler steering design. The main disadvantage of the outboard is the placement of all components at the stern of the craft. This will make it more difficult to balance the weight and achieve an ideal center of gravity.

After much discussion it was decided that it would be more efficient to go with an outboard setup. Through research we found prefabricated electric outboards. The weight of these outboards was too heavy for our application. To overcome this obstacle we decided to purchase existing lower units, and attach an electric motor to them. We found that by doing this we were able to keep the outboard lighter than the manufactured setup.
The motor selected was a Lynch LEM-200 permanent-magnet, variable DC motor. This motor is capable of efficiencies of up to 92 percent.

Power system

The batteries used during the endurance event are limited by competition regulations. Figure 8 lists the Solar Splash requirements regarding batteries[3].

7.1.2 Solar Endurance - ...Solar Endurance craft are allowed to carry 31 kg (68.2 lb) of lead acid batteries…

7.4.4 "Source Voltage" - May not exceed 36 VDC nominal value (usually 3 batteries). A maximum open circuit voltage of 52 VDC for the photovoltaic charging devices is allowed.

7.12.2 Battery Type - Only secondary (electrically rechargeable) batteries are permitted. Fuel cells, primary batteries, or mechanically rechargeable batteries will not be approved. The batteries must be commercially available, lead-acid, unmodified with their weight consistent with the Rules. Batteries must be absolutely stock (as manufactured) in every sense. The battery modules may not be modified in any manner, including the addition of electrolyte additives, case modification; or plate addition, removal, or modification.

7.12.3 Battery System - Batteries must be enclosed in one or more battery boxes or a portion of the hull to separate them from the skipper. Battery enclosures shall be equipped with a forced ventilation system, rated to at least 10 cfm. It must operate whenever the battery system is electrically connected to the craft. If the batteries are in an open area of the craft (such as on deck), forced ventilation is not required but all ventilation systems must exhaust to the rear of the craft, aft of the skipper. The batteries and their containers must be secured in such a manner that they remain in place if the boat capsizes (see 7.15.2). All electrical cables must be properly sized to expected system currents.

7.15.2 Batteries - Batteries must be secured to the hull. This must be done with a strap not less than 1¼" in width, or other hold-down device, that will not allow the battery to come loose if the boat capsizes. Velcro is not acceptable. There are two purposes for the battery container(s): 1) simplifies securing the batteries so they cannot leave the hull in the event of a capsize, and 2) if the battery case fails, causing possible escape of the electrolyte, the electrolyte will be contained in the battery container(s). Container(s) may be plastic, fiberglass, or similar composites that will not chemically react rapidly to battery acid.

Figure 8 Excerpt from Solar Splash regulations about batteries

With these rules in mind, the batteries used in the design should be those that store the greatest amount of electrical energy. Because the weight of lead-acid batteries is generally proportional to the amount of energy storage, the ideal batteries will weigh just under the required weight limit.

Through in depth research of different battery manufactures we developed a chart plotting the performances of different batteries based on the information provided from the manufacturers; see Figure 9. In choosing a battery we had to look at the demands for the different aspects of the race. It was decided that a 24 volt system would be the most efficient for the endurance, and a 36 volt system for the slalom and sprint. With weight being a critical issue it quickly narrowed down the choices.

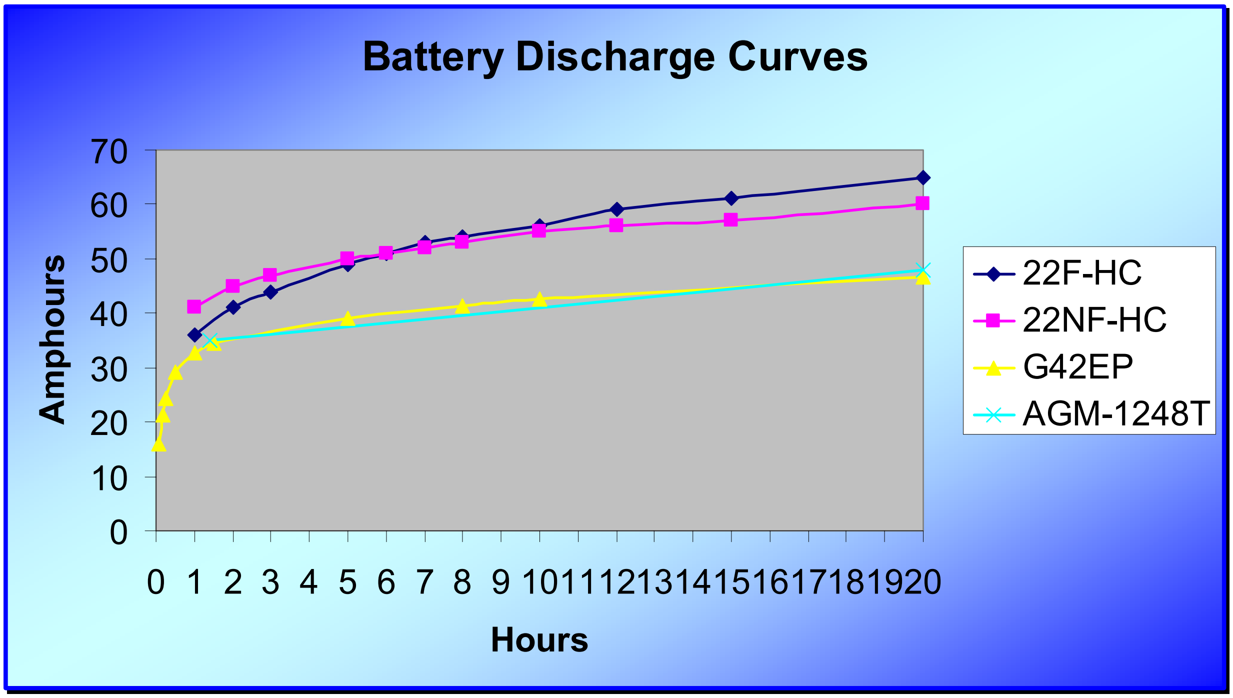

Figure 9 Battery discharge comparisons for U.S. Battery, Hawker Energy Batteries, and Concorde Batteries

We chose to run the US battery model number 22NF-HC for the endurance portion of the race. This battery proved best for a 24 volt set up[5]. As for the slalom and sprint we decided to use the Optima Red Top. We chose the US battery for its high amp hour characteristic and its weight. The Red Top was chose due to its high rate of discharge, which is convenient for the sprint.

The US battery 22NF-HC weighs 34 pounds which is appropriate for the 24 volt endurance set up. The Optima Red Top weighs 33.1 pounds which will be incorporated into the 34 volt sprint set up. By using three of the Red Tops we will stay under the maximum allowable weight for the sprint. We have not yet finalized our method of securing the batteries to the hull.

Solar array

The design of the solar array is a major contributor to the performance of the craft. With our type of craft, we do not want to have any overhanging solar panels. When installed for the endurance event, we wish to retain the aerodynamic properties of the hull. Whichever panels we choose have to be incorporated into our existing hull shape. Attaining the maximum allowable power from the array will require optimized use of the limited surface area. Another goal of the design is to keep the array light weight.

Our team researched three different types of solar arrays. They were the following: pre-manufactured panels, individual cells, and flexible panels. Each one had its advantages and disadvantages. The pre-manufactured panels were efficient, but heavy. The individual cells would have to be soldered together and then sealed to make an array. These cells were extremely fragile and hard to work with, but more efficient and light weight. The flexible panels were light weight but the power to size ratio was not desirable for our application.

Picking the solar array for this application was a challenge. The maximum 480 watt power rating for the array was only achievable by creating a custom array using the individual solar cells. This method will also allow us to keep the original streamlined aerodynamic profile. Using the individual solar cells, more of the surface area can be utilized.

The proposed design uses solar cells manufactured by Silicon Solar. They are 5 x 5 inch square cells, made of mono-crystalline silicon. The ratings for voltage and current are .54 volts and 4500 milliamps, respectively. This makes the power output for each cell 2.43 watts. For a maximum power output close to 480 watts, 195 individual cells are used with 65 cells in a parallel branch. Each branch will be rated at 35.1 volts and 4500 milliamps. For the three parallel branches, the total current will be rated at 13.5 amps. For optimal use of PV power, a maximum power point tracker will be used to adjust charging characteristics. The tracker we have decided to use is a Mini-Maximizer from AERL. This model of tracker has the most efficient conversion method of any tracker available. Also, the components are housed in compact race-trim, designed for use in solar vehicle competitions.

Conclusion

The details documented above are like puzzle pieces that form a picture of the learning process. First a challenge or assignment is made; in this case, build a more efficient solar boat. Questions arise from that challenge. What makes a boat efficient? What materials and components do we use and why? How do we build it? Research must be done to find the answers to these questions and more. Once a topic has been researched to the best ability of the students, decisions can then be made about what materials and procedures to use, and an understanding of why they were chosen as the best, or most efficient answer. Decisions then become actions, and the boat begins to take shape. The detailing of this process in written form becomes the technical report submitted to the Solar Splash competition for judging.

The senior leaders of the team benefit greatly from this project. They received a stipend from the Undergraduate Research Council at MTSU to undertake the research necessary to build the solar boat. As team leaders they learned project management and decision making skills while exercising their classroom knowledge. The seniors also receive capstone course credit for the design and construction of the boat. The freshmen, sophomores, and juniors benefit under the direction of the seniors. They become exposed to the research process and witness first hand the engineering principles they are being introduced to in the classroom.

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