The Preliminary Design Phase – The Key to Achieving Project Objectives

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Abstract

The development of a complex product, such as a new gas turbine, begins by setting overall performance specifications based upon market demands. To achieve those specifications, individual design groups, or teams, are tasked with meeting certain performance goals for engine subsystems. The overall engine performance specifications can only be achieved if the individual groups each meet their design objectives. The Cedarville University Solar Boat Team has followed a similar project management approach and has been highly successful in the world of solar boat racing. Each year, the team identifies performance goals that are necessary to win. From these, the team creates a "Power Budget" that follows the power flow through the system. For each subsystem, or component, design goals are set to determine how much power will be available to it, what efficiency it must achieve, and the power it will deliver to the next subsystem downstream. The only way the boat can meet its winning design objectives is for each subsystem to meet its own performance specifications. This paper explains how the Power Budget is used in the Preliminary Design Phase to set performance specifications for boat subsystems and provide realistic design goals for individual team members.

Keywords: Preliminary Design, performance specifications, Work Breakdown Structure (WBS)

1 Introduction

The "Preliminary Design" phase of a project refers to the initial work where performance goals are set for individual subsystems that will allow the final product to meet its overall performance specifications. This paper describes how the preliminary design phase is used in the development of solar boats in a capstone senior design experience for mechanical engineers. The authors are faculty advisers to the boat team and the procedure described here closely mirrors that which we have experienced in industry. Specifically, an example from the gas turbine industry is used as the industrial model, and the parallel use of the "Preliminary Design" phase for the solar boat is documented. Following this approach has produced two important benefits. One, the students are better prepared for industry having experienced the systems approach to product design. Two, the solar boat team has been very successful since this systems approach has allowed each design group of the team to have clear, quantified performance objectives for its subsystem.

1.1 Project Management

The Project Management Institute (PMI) in its Guide to the *Project Management Body of Knowledge (PMBOK)* provides a detailed description of the project management process (PMI, 2004). The concepts discussed in this paper are most closely related to *Step 5.3 Create a Work Breakdown Structure (WBS)*, which describe the process of breaking down a project into smaller, more manageable tasks. *Step 5.1 Collect Requirements* is also a key part of our process, but the major focus of this paper is to merge the concepts of *Requirements* from 5.1 to the *WBS* of 5.3. Specifically, we are interested in establishing performance requirements for every level of work in the *WBS* and demonstrate that only by achieving these individual specifications can we achieve our overall goals established in 5.1.

The concept of *Work Breakdown Structure* was formalized using *Project Evaluation and Review Technique (PERT)* developed by the United States Department of Defense (USDoD) (Fleming, 1998). Since that time, the process has been continually improved and has resulted in numerous military specifications for project management. While the subject of this paper is described in the context of *WBS* terminology, some of the concepts described in the USDoD specifications are used to describe our process.

1.2 The Solar Boats

There are two competitions in which the solar boat team has participated: Solar Splash (USA) and the DONG Energy Solar Challenge (DSC) in the Netherlands. In each competition, the teams enter an electrically-powered, piloted craft; the energy is provided by solar panels. Solar Splash is a multi-event competition with high speed, short distance

events (50 km/hr, 300 m) and slower, longer races (12 km/hr, 50 km). The DSC is a 5 day race following the Elfstedentocht course of 220 km with speeds of 15-20 km/hr. The *Elfstedentocht* (Eleven City Tour) is a famous Dutch skating race that circumnavigates the canals and lakes of the Province of Friesland. Solar Splash is open only to universities from around the world, while the DSC is open to both academic and industrial teams. Important elements of a successful boat are the solar panels, peak power tracker, batteries, motor controller and motor, drive train, propeller, hull, and energy management system.

To better understand the subject of this paper it is helpful to review the various components of the solar boats. Figure 1 shows a schematic of the boat and identifies the key components. Understanding the flow of energy through the system is instrumental in understanding our approach to preliminary design.

The boats receive energy from two sources; solar panels (photovoltaic (PV) array) and batteries. We look at energy at a moment in time, and thus we focus on power instead of energy. Circled numbers refer to components shown on the diagram of the boat.

1. Power supply

   1a. Power draw from the solar panels① is controlled by the Maximum Power Point Tracker (MPPT) ② whose function is to control the output current to ensure that the maximum possible power is derived from the panels.

   1b. Power is also supplied from Li-ion batteries③. The batteries have a complex Battery Management System (BMS) which includes a microprocessor that controls charging and discharging of the batteries.

2. The Energy Management System (EMS) ④ controls the overall energy flow on the boat. The EMS receives information from various sensors throughout the boat (voltage, current, power, speed, position, solar insolation, battery status, etc.) and driver input. The EMS then determines how fast the boat should go in order to finish the current leg of the race in the shortest amount of time with the solar power available and energy remaining in the batteries.

3. The Motor Controller⑤ receives commands from the EMS and/or the driver and determines the proper motor speed.

4. The motor⑥ supplies power to a gearbox⑦, which then supplies power to the propeller⑧.

5. The propeller provides thrust to the boat whose speed is constant when the thrust of the propeller matches the drag of the hull ⑨.

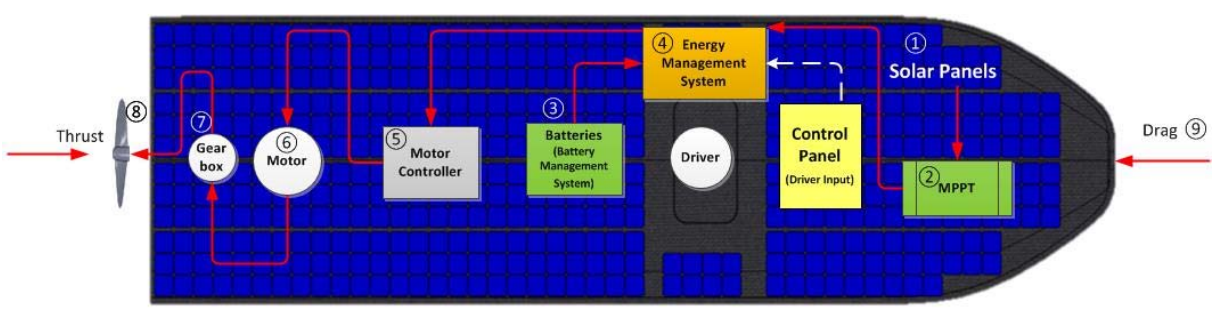

Figure 1: Layout of Solar Boat with Systems and Power Flow

1.3 Gas Turbine Engines

Gas turbine engines are very complex machines. For the purpose of this example, we will just focus on three major sections of the engines: the compressor①, the combustor②, and the turbine③. The compressor takes in the air and dramatically increases the pressure. This is done in a number of stages (rotors with blades) and requires work done by the turbine. The compressed air enters the combustor where it is mixed with fuel and ignited. The temperature of the gas now increases substantially while the pressure is relatively unchanged. The hot gas then enters the turbine. First, energy is extracted from the gas in the stages of the turbine. In the jet engine shown, the only energy extracted is for the work necessary to drive the compressor; the remaining energy in the gas is extracted

in the form of forward thrust as the gas is expanded leaving the engine. The two key performance specifications for a jet engine are thrust and thrust specific fuel consumption (TSFC), a measure of efficiency.

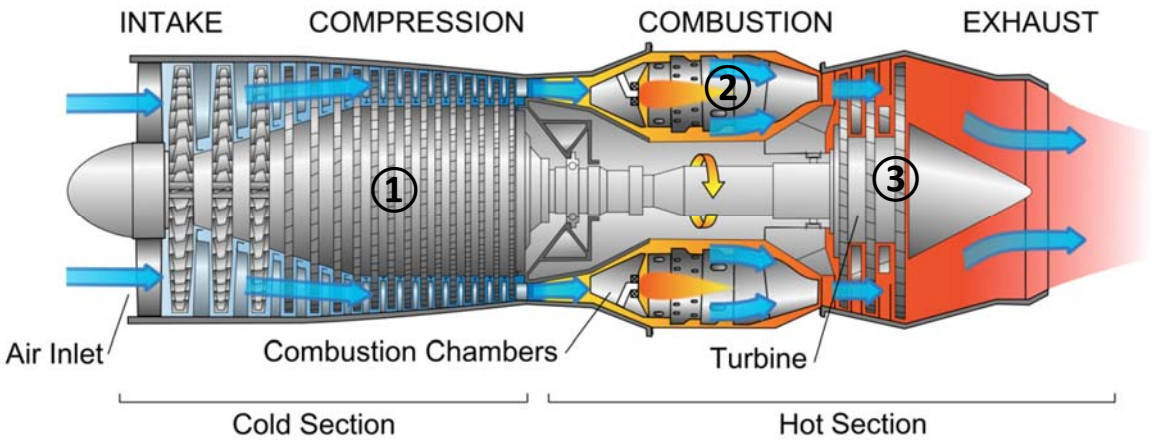

Figure 2: Gas Turbine Components (Dahl, 2007)

1.4 The Mechanical Engineering Senior Design Course – Project-Based Engineering Education

The mechanical engineering program at Cedarville University requires a "capstone design experience" which involves the design, manufacture, and testing of a product. This experience includes two 3-credit courses; one in the fall semester, one in the spring semester of the senior year. The students from these courses primarily choose to work on an intermural competition team, and it is from these students that the solar boat team is formed. Thus, each year, the team is almost entirely composed of mechanical engineering seniors who have no experience with the project.

As students enter the capstone experience, they must set performance specifications for the team as a whole. These specifications, or goals, are in line with *5.1 Project Specifications* of the *WBS*. The setting of these overall goals is not the main subject of this paper. However, they are the starting point from which we derive individual goals and specifications and begin the process of "preliminary design."

2 Preliminary Design

The Preliminary Design phase is much like the budget stage of project management. The PMBOK specifies a cost identification process, specifically *Steps 7.1 Estimate Costs* and *7.2 Determine Budget*. The budget process involves a detailed breakdown of anticipated costs and sets limits for individual systems. Likewise, the Preliminary Design phase set limits (performance specifications) for individual systems. In fact, in our boat project we have both a "Power Budget" and a "Weight Budget" in addition to the budget for the financial costs of the project.

Setting specifications in a budget can be both constraining and freeing. Performance specifications for a new product, or for a racing boat, are often optimistic since they are chosen with an objective of outperforming the competition. In this way, engineers are often overwhelmed when first faced with these specifications. However, these specifications can also be liberating. When an engineer is faced with non-quantified objectives such as "efficient as possible," "maximum power," "minimum weight," "as good as possible," etc., the task is never done. The product could always be made more efficient, more powerful, lighter, etc. Coupled with a Continuous Improvement philosophy and unspecified objectives, the work must go on and on. Clearly setting performance specifications allows a design group to know when the task is complete, when to stop development, and when to deliver the product.

Design specifications are also liberating in that they do not specify how these goals are to be met. Thus, a design group has the freedom to pursue unconventional methods to meet these goals; the engineers are not constrained to do things in a particular manner.

Performance specifications also provide protection for engineers and individual design groups. When an overall product fails to meet its performance specifications, there may be significant repercussions for the designers. If a

design group has met the performance objective for its component, and has the experimental data to prove it, then that group is absolved of any blame for the failure of the system as a whole. This is a tremendous protection for these engineers. Failure to meet product specifications can result in serious damage to an engineer's career.

We now present an example of the "Preliminary Design" approach used in industry and then show how we have implemented this approach for our boat team.

2.1 Preliminary Design - An Example from the Gas Turbine Industry

The following example is a qualitative description of an actual design experience of one of the authors while working in the gas turbine industry. When developing a new gas turbine, performance specifications are set that will allow the product to be competitive (Brooks, 2000). While the number of specifications can be onerous, we will deal with only two in this example: thrust and thrust specific fuel consumption (TSFC). Other major concerns include weight and cost.

Figure 3 shows a schematic of a gas turbine engine, with the three major components of Figure 2 shown as subsystems of the overall product. The setting of overall performance specifications is governed by market factors; most engineers do not usually take part in this process. At some level, however, engineers may be involved in that the specifications must be kept within reason. However, our experience, and those of other engineers, has often been that these performance specifications are highly optimistic. Regardless, these overall goals are set to provide a competitive advantage in the market, and these goals drive the design of each of the individual components. *Step 5.1* of the *Project Management Process (PMP)* gives guidelines for the development of these specifications.

Typically, the *Work Breakdown Structure (WBS), Section 5.3* of the *PMP* is already set for individual groups in a well-established industry (Ivanov, 2013). What are new with each product are the performance specifications for each individual system. These specifications are set in the "Preliminary Design Phase," which is a critical step that must not be neglected in the *WBS*.

The overall performance goals of the end product (thrust and TSFC) are not the responsibility of any subteam working on the individual systems described in the *WBS*. No group, regardless of how well it designs its system, can achieve the overall specifications of the project. No group has the responsibility to produce a certain level of TSFC (e.g. a combustor cannot alone meet this goal). So what is the responsibility of each individual design group? Each system that makes up the product must meet the individual performance specifications set in the preliminary design phase.

In our example, this phase begins with the overall product specifications of thrust and TSFC, but these are then translated into specifications for each of the three major systems (compressor, combustor, and turbine). Figure 3 shows some of the primary design variables (specifications) for each of the three systems. In a gas turbine engine, these are typically pressure P, temperature T, and mass flow rate $\dot{m}$.

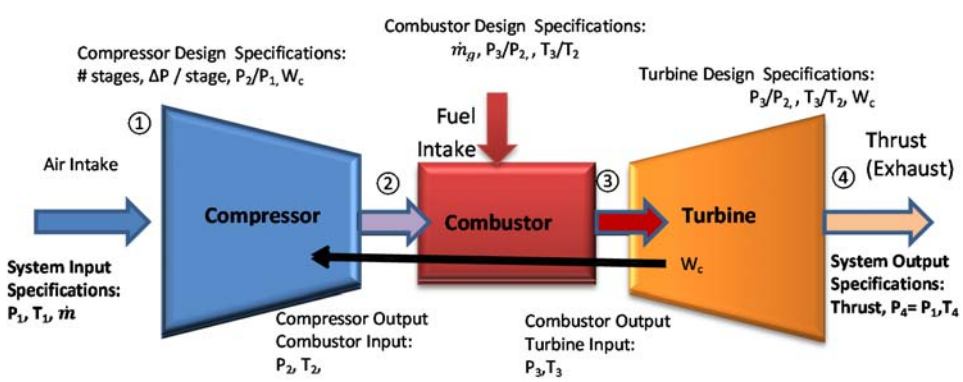

Figure 3: Gas Turbine Schematic with Design Variables.

Often, when setting specifications for subsystems, it is easiest to start at the overall product goals. For the gas turbine, where thrust is a major product specification, this thrust must come from the turbine, and thus one performance specification is already set for the turbine subsystem. However, to produce that thrust, the turbine needs a certain amount of energy entering into it and it needs to operate at a certain efficiency. The input energy achieved by setting a mass flow rate, pressure, and temperature for the gas leaving the combustor and entering the turbine; the efficiency is a performance specification that the turbine design group must meet.

In the preliminary design stage, these inputs to the turbine must be specified based upon previous knowledge of turbine performance and planned improvements. Designers must also consider the work to be extracted from the gas in the turbine W_c that is needed to drive the compressor. Most efforts to improve turbine performance focus on increasing the temperature of the incoming gas. The upper limit of turbine inlet temperature is limited by the material properties of the turbine components.

Once the specifications for the turbine are determined, those for the combustor must be set. Again, input specifications for the combustor are determined by output specifications and knowledge of combustor performance. In order to produce the amount of gas at the energy levels needed for the turbine, the combustor must have a certain mass of compressed air delivered from the compressor, it must have a certain amount of fuel delivered to it, and it must burn this fuel efficiently. Thus, the performance specifications for the combustor, including inlet gas temperature and pressure as well as fuel mass flow rate and combustor efficiency, are established.

Finally, the compressor specifications must be determined. Knowing the outlet specifications required for the combustor, helps the designers specify the compressor input conditions of air mass flow rate as well as performance specifications including the pressure ratio of inlet and outlet pressures and the efficiency of the compressor; the efficiency determines the work the turbine must provide to drive the compressor.

In setting the specifications of each system, the designers use their extensive experience of gas turbines and couple this with a knowledge of possible improvements in an effort to reach a higher level of performance. The goals set for each system reflect this continuous improvement; the specifications require that each group improve upon previous designs.

Each design group is responsible to meet the specification of its particular component or subsystem. As stated before, no design group has the responsibility to meet the overall system performance specifications. However, each group must meet its own design objectives, for without that, the overall product will fall short of its performance specifications.

Just as performance specifications must be clearly quantified for the overall product, performance specifications for the individual systems must also be clearly quantified. Clearly quanitified performance specifications allow each group to measure its performance and to know when it has achieved its objectives.

As an aside, we have seen many cases in industry, where the engineers' response to the results of the Preliminary Design Phase is one of incredulity. Sales personnel often agree to overly optimistic performance specifications when working with a customer. Managers often anticipate significant improvement in performance over past models. The engineer, whose career may hinge upon meeting these specifications, often accepts them with reluctance and apprehension.

2.2 Preliminary Design – Applied to the Solar Boat Project

We have adopted a systems approach for the solar boat in which we break down the boat into smaller systems as described in a *WBS*. A key to our success as a team has been how we set performance specifications for each of these systems and follows our industrial experience closely.

While our industrial example of a gas turbine engine was qualitative in nature due to proprietary information, the implementation in our project-based engineering education can be quantified and easier to follow. To start, we set our overall performance specifications to win the race. In *Step 5.1* of the *WBS* a description of the process of setting specifications is given; our one goal is to win our race. To do this, we determine a speed that we think is sufficient to win. We review races from previous years, determine the speed of the winning boat, add a moderate improvement to that speed, and specify that as our primary performance specification. For the DONG Solar Energy Challenge, we determined that a speed of 20 km/hr could position us to win the Open Class. However, it must be realized that no individual or subteam is responsible to meet that goal. Each design group must have its own set of specifications for its system. When each design group meets its individual goals, then the team as a whole may meet its goal of winning the race. However, it is important to note, that even if we meet our speed goals, we might not win the race. If another team competes with a boat that is faster than our specification, we cannot win, but that is outside of our control.

Figure 4 is an enhanced version of the solar boat shown in Figure 1. Here, the power flow through the boat systems is graphically represented by the thickness of the red arrows between components; the thicker the line the greater the power flow. Note that as the power flows through the boat systems, part of it is lost due to inefficiencies in each

component; the lines get narrower as the power progresses downstream. We use this visual to illustrate our "Power Budget," which is the main tool of our preliminary design phase. Figure 5 provides the same information in a flow chart.

Each team in the competition is limited to a certain amount of solar power capacity (1750 watts) under standard conditions, and a limited amount of energy stored in batteries (1 kW-hr). This is the starting point of our power budget; it is not the amount of power the propeller will have to push the boat forward.

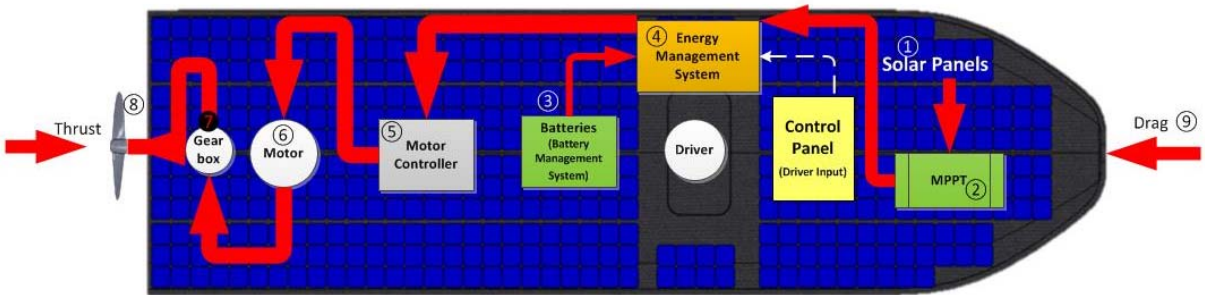

Figure 4: Solar Boat with Power Flow (Magnitude of power indicated by line thickness, Direction by arrows)

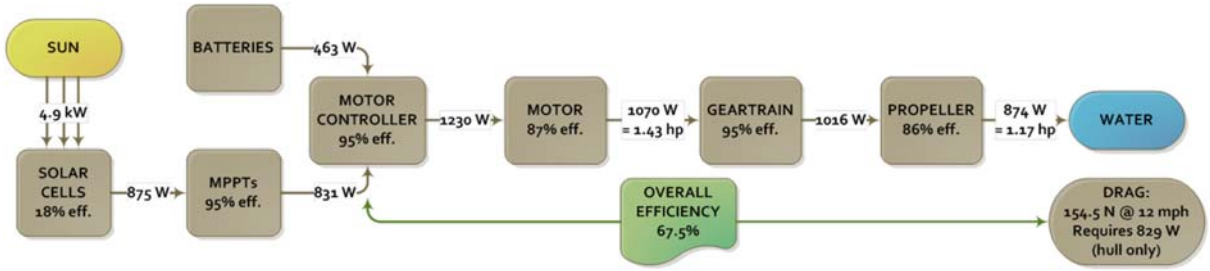

Figure 5: Power Budget for Solar Boat

We now give a summary of how we proceeded to establish performance specifications for each system of the boat during the preliminary design phase. Our starting point was the input power available. From there, we set efficiency goals for each individual system (or component), which gave us power out of that system and into the next; we tracked this power till we got to the propeller. This process is visually represented in Figures 4 and 5, and is described in detail now. The power flow through each component is described and the performance specifications for each component are highlighted in boldface.

1a The sun does not always shine at "standard conditions" (1000 w/m^2), especially in the Netherlands. Thus, we researched the solar insolation in the Netherlands during the July and determined that in those conditions we would probably get approximately **875 W** from our **solar panels**; not the 1750 W they could produce under ideal conditions. This power would be at **50 volts** and **17.5 amps** and then pass through our MPPT.

We set out to design and build our own **MPPT**. Based upon our use of MPPTs in the past, we felt confident we could produce an MPPT with **95% efficiency**. Thus, we set this as our performance goal. The MPPTs must handle up to **1750 watts** (ideal conditions) at **50 volts**, and deliver this power at a charging voltage of **21 volts** to the batteries, or 18 volts to the motor controller. This set a difficult performance specification of **100 amps**.

1b The energy stored in the **batteries** was limited to **1 kW-hr**. Based upon the length of the course, we determined the rate at which we could draw this energy (power) at a given speed; this was an iterative process. For this example, we determined we could draw **463 watts** over the course of the race.

2. During the race, the **motor controller** regulates the power delivered from the batteries and solar panels to the motor. The motor controller is governed by input signals from the Energy Management System (EMS). Our motor controllers have been very efficient, so we felt an efficiency of **95%** was achievable. Thus, the power delivered to the motor itself in our design specification is **1230 watts** at **21 volts** and **60 amps**.
3. We had recently built a **motor** for our boat and purchased a **gearbox** to reduce the speed of the propeller. We had found that the motor-gearbox combination was about **83% efficient**, so we should be able to deliver **1000 watts** to the propeller.

   However, the motor differs from all the other components up to this point in that the input power is in the form of electrical energy while the output power is in the form of mechanical energy. Thus, the input specifications for the motor and gearbox must include voltage and amperage requirements (**21 volts, 60 amps**), while the output is specified in terms of torque and RPM requirements (**1000 W, 600 rpm, 16 N-m**).
4. From our history of **propeller** design and manufacture we know that we can make propellers that are about 80% efficient. To do this, we maximize the diameter and slow down the rotational speed of the propeller. For this race, we decided to increase our efficiency goal up to **86% at 600 RPM and 16 N-m or torque**. This would give us output specifications of **830 W**; based upon our speed specification of **20 km/hr**, our propeller would be able to provide a thrust of **150 N**. This was a very optimistic specification for propeller performance.
5. Thus, to achieve our overall design goal of **20 km/hr**, with a propeller producing 150 N of thrust, our **hull** had to be designed to have no more than **150 N** of drag at that speed.

By setting these individual goals for each system on the boat, we set realistic expectations for each design group. Some of these goals would be harder to achieve than others, but everybody had a target for which to aim. By following this process, no group had to be concerned with meeting the overall speed objective (nor could they). Also, each group could define an end point to their work instead of following the never ending process of “minimizing” or “maximizing” the performance of their system.

Unlike industry, we find that students are overly optimistic in the preliminary design phase and set unrealistic goals. They also want to do more than is possible; they often don’t understand the amount of work necessary to actually meet these expectations. It is the adviser’s role to help the students realistically scope the project. Similarly, we have often noticed that by the end of the project the roles are reversed; the students, faced with reality, suddenly lower their expectations to an unacceptable point. Here, it is the role of the adviser to maintain a level of commitment to the original product specifications.

The preliminary design phase also has helped us set other specifications for the individual components. While we have focused on efficiency here and power flow, it is also imperative to match components to each other. We can’t have a propeller designed to run at 600 RPM driven by a motor and gearbox delivering power at 1000 RPM even if the power output of one matches the power input of the other. Likewise, the output voltages and currents of the MPPT’s must match the input voltage and current of the motor controller. Specifications like this must be matched throughout the boat which is why the preliminary design phase is imperative.

2.3 Preliminary Design – Flexibility

The performance specifications for each system are developed using the best resources available to the team. However, individual groups may not be able to meet their objectives, or they may find that a change in specifications would allow them to greatly improve the product as a whole. Thus, the specifications set in the Preliminary Design Phase should be somewhat flexible. Elsewhere, we describe a specific example of this where our propeller designer asked for a change in the shaft speed (Dewhurst and Brown, 2013). She noted that a 25% reduction in shaft speed would allow a 4% increase in propeller performance. The motor group found that a 25% reduction in speed caused an efficiency loss of 2%. As a group, we were able to readjust the performance specifications of both groups concerning shaft speed to gain a 2% improvement in overall system efficiency.

Figure 6: One of the Authors (Brown) Driving the Solar Boat at the DONG Energy Solar Challenge.

3 Conclusion

The Preliminary Design Phase is critical to the success of a project. This practice is carried out in industry, and we use a similar approach in our capstone design experience. While this has a significant role in our team's success, it has also served to better prepare our students for industry by helping them to understand this vital part of the design process. A number of graduates have given us valuable feedback saying that this systems approach to product design is what they are now using in industry.

The Preliminary Design Phase is a budgeting process that sets performance specifications for individual components of a larger system to enable the overall system to meet prescribed performance specifications. This process is demanding yet liberating for engineers as it sets optimistic goals, but also provides clear measures of accountability.

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