USING THE SOLAR SPLASH COMPETITION TO TRAIN THE NEW GENERATION OF MARITIME ENGINEERS IN SOLAR POWER USE

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ABSTRACT
We present a program (UNM Solar Splash) developed at the University of New Mexico with the goal of training engineering students in building solar-powered watercraft. The program is run as a hybrid between a senior design capstone course and a graduate problems course. It is motivated by the pressing need to minimize the environmental impact of maritime transport, in particular, the reduction of greenhouse gas emissions. One of the most promising ways to address this need is the expansion of solar-powered water transport. To support such an expansion, we need to train a new generation of specialists with a synergy of skills in mechanical and electrical engineering. Each year, the student team builds a solar–electric speedboat to participate in an international student competition. What distinguishes our program from the competitors is the collaboration of advanced undergraduate and graduate students with majors in both mechanical and electrical engineering.
Keywords: engineering education, solar power, renewable energy.

1 INTRODUCTION

The Paris Climate Agreement sets the goal of limiting global warming to "well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C" [1]. Among the targets that must be met to reach this goal is the reduction of greenhouse gas (GHG) emissions, which must reach net zero in the second half of the 21st century. Serious concerns have been expressed regarding the ability of the transportation sector to meet its share of the reduction goals. Should the current growth trends continue, by 2050 aviation and shipping combined would account for between 10% and 32% of the total CO_2 emissions in the 2°C scenario [2]. For comparison, their mid-2000s combined share was 5.3% [2]. To contain the relative contribution of shipping to GHG emissions while maintaining the growth trends essential for the global economy, a qualitative transformation of shipping and related technology must happen in the immediate future.

A variety of GHG emission mitigation measures has been considered for the shipping industry [3], including installation of a solar-power system, a fuel cell, optimization of hull design, and reduction of cruising speed. Cost analysis was conducted for two test-case scenarios – a 74,000 DWT (deadweight tonnage) bulk carrier and an 8,000 TEU (20 foot equivalent units) container ship. The study [3] did not find the solar retrofit to be the most efficient, but the constraints imposed upon the system the authors considered (40 kW used for auxiliary propulsion) may not be realistic for the current state of the art, although it is based on a real-life example: the Auriga Leader solar power-assisted ship [4]. For example, consider a New Panamax container ship [5], with representative dimensions as follows: 360 m length, 50 m beam. The approximate area available for the solar panels (taking into account the narrowing of the deck at the bow and stern) is 15,500 m^2, so assuming 900 W/m^2 insolation, tracking panels, and 30% conversion efficiency, such an array would produce 4.185 MW, likely with considerable economies of scale in cost per kilowatt. Note that this value still does not compare favorably with the internal combustion engine power typical for a container ship of this class (20 to 70 MW).

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It must also be mentioned that solar power in shipping industry may appear in two very different contexts: as a retrofit of / supplement to existing design and as the key part of a new design, such as the Hidrocat project [6]. The former context is very important but may be beyond the scope of this paper for reasons described below. A recent review of the latter context can be found in [7], which also mentions Solar Splash.

Solar Splash is an annual international intercollegiate solar/electric boat regatta established in 1994. It is typically held in the format of a five-day competition of solar/electric boats built by student teams in the months before the competition. The competition includes a qualification event, a sprint, a slalom, and an endurance competition. Teams also receive scores for build quality and for technical reports submitted before the competition.

This paper describes our experience of participation in Solar Splash at the University of New Mexico. Such an experience can be very beneficial for the new generation of students who will become the engineers who must confront the task of developing ships of the near future with radically reduced emissions profile being one of the design constraints. This task remains quite challenging – presently the largest fully solar-powered sea vessel is Tûranor PlanetSolar [8], with only a 31 m length. On the other hand, its seaworthiness was proven by a 60,000 km circumnavigation. Making international shipping more environmentally friendly, especially in the context of reducing GHG emissions, is a very challenging task. Addressing it with new designs is both less of a challenge than a retrofit of the existing ships (which may not be even feasible) and more aspirational. Accordingly, such new designs provide the aspirational focus of our Solar Splash program described below.

2 SOLAR SPLASH – COMPETITION HISTORY AND RULES

The Solar Splash intercollegiate solar/electric boat competition was established with a broad educational goal: “to promote student interest in solar energy, both as an energy source and in its engineering applications” [9]. The competition was established in 1994 [10] and was originally led by Marquette University. It moved from Milwaukee, Wisconsin to New Orleans in 2000, to Buffalo, New York in 2001, to Fayetteville, Arkansas, in 2006, and to Cedar Falls, Iowa, in 2011. After 2014, the competition was held in Ohio – first in Dayton, then in Springfield. Since its inception, the Solar Splash featured a combination of scored events including actual competitions (sprint, slalom, endurance race) and providing proper consideration to such important aspects of engineering experience as writing a design report, passing compliance tests for all design and safety rules, and making a presentation of the technical features of the design. Additional points are also awarded for overall workmanship.

The rules of the competition have changed several times to address various concerns. For example, originally it was possible to develop and use separate propulsion systems for the sprint, slalom, and endurance events, raising concerns about the practicality of the overall design [9]. Currently these concerns are addressed by restrictions on reconfiguration: no components may be physically removed from the boat in the course of the competition. The only two exceptions are the batteries – two sets are allowed – and the solar panels, which can be removed for the sprint and slalom events. Components such as motors, propellers, and rudders can be swapped out, but any such swap carries a weight penalty, because while parts can be rearranged, they cannot be physically removed from the boat: for example, if you have different propellers for sprint and endurance events, you must carry the sprint propeller on board during the endurance race.

The competition organizers have also taken an effort to make it relatively easy for new competitors to enter with a modest (around USD 5,000) initial investment by deliberate restrictions on some potentially expensive high-tech components: for example, only lead acid batteries are allowed for energy storage, and their total weight is restricted.

3 UNM SOLAR SPLASH – HISTORY AND DISTINCTIVE FEATURES

The University of New Mexico was a relatively late entrant into Solar Splash, fielding the first team in 2016. Our first entry was not exactly sophisticated: it used a second-hand aluminium jon boat hull with modest efficiency (19.65%) consumer-grade monocrystalline photovoltaic cells (Everbright Solar) mounted on a wooden deck covering most of the upper surface of the boat, leaving only a modest asymmetric space for the skipper cockpit (Fig. 1).

Figure 1: UNM Solar Splash 2016 boat. In the cockpit: Joshua Montoya (skipper), at the stern: Joshua Stewart (electrical team lead).

What distinguished the 2016 design was its aggressive simplicity, which resulted in a relatively low weight. We were also able to use the allowance provided by the rules for student-fabricated solar panels: while prefabricated panels are capped at 480 W output, student-built panels are allowed up to 528 W. An important additional contribution to the solar array was provided by installation of bypass diodes between multiple strings of solar cells to minimize power losses due to partial shading. In combination with mass savings due to minimalistic design, the flat-bottomed hull also provided excellent performance in the slalom event, resulting in a podium slalom finish (second place) and fourth place overall, as well as an award for the best rookie team. 2016 also began the tradition of collaboration between ME and ECE departments, which quickly became indispensable to the success of our program.

The motor and drivetrain configuration of the 2016 boat (Fig. 2) was conceived around a Motenergy Brushless Permanent Magnet AC (PMAC) ME1117 motor, which was chosen because of its high efficiency, around 90%, and rated at 15 peak (6 sustained) horsepower. The team considered a choice of two designs: an inboard and an outboard motor. While an outboard motor is less expensive and lighter, an inboard motor was selected as a better fit for the hull due to its greater available power and more favourable weight distribution.

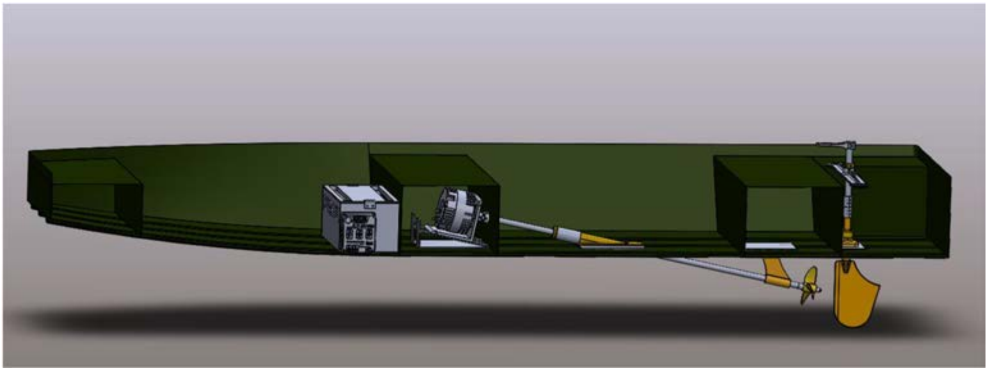

Figure 2: Rendering of the original design of the motor and drivetrain of the 2016 boat. Credit: UNM Solar Splash 2016 team (G. Cearley, K. Diamond, L. Henrion, R. Baca, S. Shin, S. Garner, J. Stewart, A. Flores, and J. Montoya).

It must be specially mentioned here that Solar Splash at UNM started not as a standalone program, but as one of the options for a capstone design course for seniors. Other options at the Mechanical Engineering department at the time included a traditional one-semester senior design course or sustained participation in a three-semester Formula SAE (Society of Automotive Engineers) program designing, building, and racing a car. From the organizational point of view, the existence of these two programs provided useful reference points. Solar Splash could not be implemented with the same timeframe and scale as the FSAE program, both due to time constraints (we literally had one semester between the decision to form a team and the competition date) and to difference in the scope of work (no suspension, no internal combustion engine, etc.). On the other hand, while a typical senior design team could be comprised of four or five ME or ECE students, the Solar Splash project was naturally interdisciplinary. Note that while this inherent feature of Solar Splash has been described quite some time ago [11], few teams feature multi-department collaborations.

We also needed a larger student group to conceive, implement, and test the design, as well as take it to the competition: eight ME and one ECE student. Finally, we had the strong support from Professor J. Wood, who had developed the capstone design course at the UNM ME department, making it possible for the students to work on the boat and learn widely-adopted engineering practices such as project management using PERT [12], CPM [13], and Gantt [14] charts, cost and manufacturability analysis, and consideration and scoring of design alternatives for each unit and the overall project with quality function deployment methods such as House of Quality (HOQ) [15].

According to the rules of the competition, in all the events, the boat had to run on solar power only – directly collected and/or stored. Much to our surprise, we found that none of the veteran teams used any kind of automation, such as MPPT (maximum power point tracking) for charging their batteries on the shore. An Arduino-based charge controller was developed by the ECE student working on the project (J. Stewart) to implement MPPT, making an important contribution to the overall team success.

Inspired by the success of our initial entry, we decided to pursue a more ambitious plan for the 2017, starting with a two-semester timetable for Solar Splash: special topics/programs courses in the fall of 2016 and capstone design courses in the spring of 2017. As several participants of the 2016 Solar Splash graduated, stayed on at UNM, and expressed interest in helping the new team, we also made accommodations for giving credit to graduate student participants, as the rules allow both undergraduates and graduates in the teams. The active involvement of graduate students became another defining feature of UNM Solar Splash, providing both expertise and continuity. Additionally, the ECE participation was increased to feature three student sub teams working on designs of the MPPT tracker, the powertrain, and the solar array.

Our goals for 2017 were also set much more ambitiously – not just to compete, but to rise to a podium (top three) finish. The 2017 team performed a thorough analysis of the boat built by the 2015/2016 champions, Cedarville University, compared it with the 2016 UNM entry, and identified several areas where improvement would make the most difference. The most obvious difference was in the hull shape and drag, with Cedarville using a home-built hybrid planing/displacement hull with a Kevlar/Nomex honeycomb core. This hull facilitated excellent performance at the endurance event, responsible for the greatest percentage in the overall competition score. Accordingly, the UNM team set the goal to select a hull that would most improve upon the performance of the 2016 boat ("The Jolly Roger"). Upon examination of the team's capabilities, a decision was reached not to fabricate the hull. Several affordable prefabricated hulls were selected for comparison: a 14 ft jon boat (reference 2016 hull), a Pacific Dory, a dinghy, and a boat originally developed by Harley Gheen Sr in Titusville, Florida, and marketed as Gheenoe [16]. It has a long, slender, shallow-draft hull inspired by the low-drag shape of a canoe but featuring an integral outrigger to improve stability. The performance characteristics analysis of the hulls (Fig. 3) included five key categories for five hulls (two Gheenoe sizes). For the "Drag" category, the team created 3D models of the hull shapes under consideration and imported them into STAR-CCM+ [17] to conduct a numerical drag study. Based on the analysis, a 13 ft Gheenoe fiberglass/composite hull was chosen as the most well-rounded option.

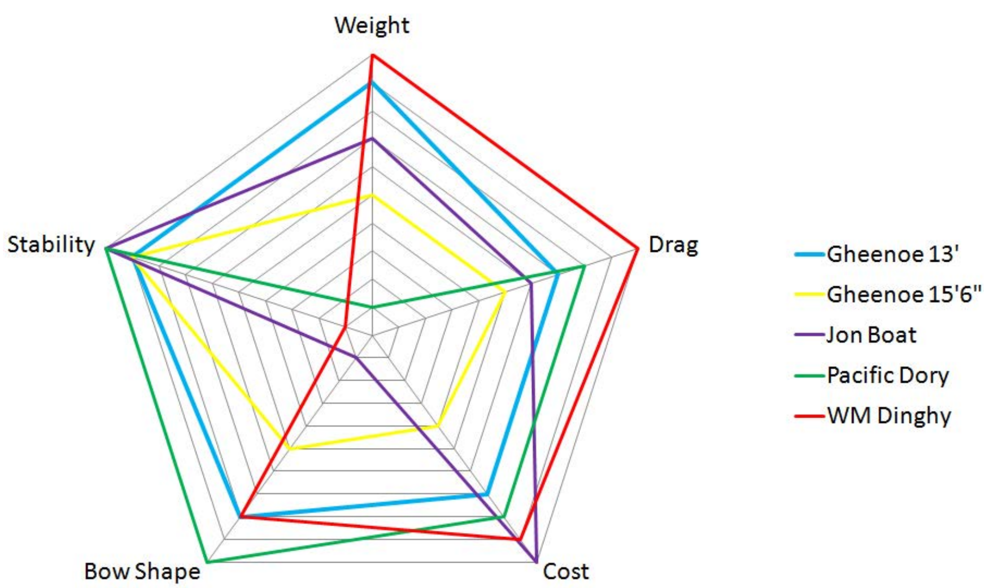

Figure 3: Hull analysis spider chart for Solar Splash 2017. Credit: UNM Solar Splash 2016 ME team (M. Anselmi, D. Taylor, D. Freelong, S. Olguin, A. Hubbard, S. Fattor, R. Muyshondt, T. Martinez, M. Fry).

Major improvements were also made to the solar tracker, the powertrain, and the solar array. A local company (SolAero Technologies Corporation) provided us with access to extremely high-performance (about 30% efficiency) solar cells, from which a new solar array was assembled.

Why then did the 2017 team only reach seventh place in the competition overall? What is inevitable for any practical engineering project is that some components fail to arrive on time, and some do not meet the specifications. Planning for such contingencies is very important, as the UNM Solar Splash team learned the hard way. The component that took a long time to arrive was the hull. In turn, that led to compressed build and testing schedules for all the subsystems including the solar array, which in turn precipitated several malfunctions during the competition that had to be resolved on the spot. For mounting the solar cells, a high-temperature HDPE (high-density polyethylene) sheet was ordered, to provide considerable structural strength and weight savings. However, after the solar cells were mounted, during the test of the array it was revealed that the material was not in fact temperature-resistant, leading to a literal meltdown and a rushed rebuild of the solar array. In a sense, the very fact that 2017 boat ("Solulfur" or "Sunwolf" (Fig. 4)) was even ready to compete is a testament to the perseverance and teamwork of the team, including the ECE students Stephen Maurice and Joshua Stewart who were rebuilding the solar array in the boat trailer as the boat was being towed to the competition. The Outstanding Solar System Design award received by UNM that year was a well-earned recognition of the students' triumph over adversity.

Figure 4: 2017 endurance race. UNM boat (number 3, seventh place finish) is overtaken by University of Puerto Rico boat (number 6, second place finish).

Another practical lesson learned was not to change too many things at once. The 2017 boat retained only one common feature with its predecessor: the inboard motor setup, which was perhaps the most questionable component: compared to our competitors, we were underpowered, and the motor controller was proprietary, which made reprogramming it on the spot impossible. Learning from the 2017 experiences, the 2018 Solar Splash team focused on incremental improvements to all components except one: the powertrain, which needed to be radically altered in terms of power, in terms of programmability, and in terms of monitoring. For the 2018 boat ("The Regulator" (Fig. 5)), a new setup was developed, with two powerful DC motors, one of them mounted in line with the propeller driveshaft and the other driving the same driveshaft via a toothed belt. This arrangement made it possible to quickly swap between two configurations: in sprint and slalom events, both motors would drive the propeller to achieve maximum speed, producing more than twice the peak power of the 2017 powertrain, and in the endurance event, the toothed belt would be removed, and the corresponding motor left unpowered to maximize battery life. For the motor controller, a cruise-control program was developed. It monitored the batteries and the total power the motor received from the batteries and the solar array and set the motor RPM to a value which would leave the batteries completely discharged by the pre-set end of the endurance event. Additional improvements included a water-cooling system for the solar array to optimize its performance and a telemetry system to log and transmit all the system states (power from the array, battery voltage, motor RPM, boat speed, etc.) in real time to shore.

Figure 5: 2018 boat during the qualifying event. Note the water-cooling system for the solar array. Skipper: Erich Brown.

Daniel Taylor, one of the 2017 team leads, deserves special recognition for serving as the instructor of record leading the ME section of the 2018 team. In the results of the 2018 competition, the UNM team had two podium finishes in the major event – second place in slalom and third in sprint, along with second place for the technical report, third place for the presentation, an award for outstanding electrical system design, a much-coveted award for outstanding workmanship, and an award to the most-improved team. The overall fourth place finish was due to the team finishing seventh in the endurance race.

In the autumn of 2017, a team of undergraduate and graduate students conducted an experimental and numerical study to determine the main factor that held our boat back in the endurance race. Of course, we had to take into consideration that our competitors also kept improving and refining their design, but as water-tunnel experiments with hull models showed and numerical simulation confirmed, the Gheenoe hull chosen in 2017 and reused with some performance modifications in 2018, despite its modest weight and excellent stability, produced appreciably more drag than narrower and longer wavesplitter hulls similar in shape to those used by the team of the University of Cedarville that won several recent events. Accordingly, a decision was made to conduct further numerical analysis and select an optimal shape for a hull of that type, using overall length and displacement as design constraints. Based on the results of that study, a hull shape with minimal drag was selected by the students to be built in the spring of 2018, using marine plywood reinforced with fiberglass (Fig. 6), with anticipated 25% drag reduction in comparison with the Gheenoe hull. Since the project again involved ordering components and materials with uncertain dates of arrival, a fallback option of using the old hull was also left in consideration. Improvements to other components, while not as radical as the new hull, should give the 2019 a good chance for a podium finish. These improvements included developing a new two-axis solar tracker, a rebuild of the solar array reducing weight and adding diagnostic features, addition of a touchscreen control panel for the skipper, and an upgrade of the cruise control system with software written in Arduino C. The rod and twist throttle rudder and motor control mechanism from the previous year was replaced with a steering wheel, which in combination with the control panel makes the boat much more comfortable for the skipper, which is important for the endurance race.

Figure 6: Construction stages of the wooden hull for the 2019 boat.

At the time when this paper is submitted, the 2019 Solar Splash regatta is yet to happen. Regardless of its exact outcome, we can conclude that the UNM ME and ECE students who participated in the project are already winners, because they successfully completed an ambitious project, learned valuable practical skills, including teamwork, and got to represent UNM in an international competition. We are quite hopeful that participation in UNM Solar Splash will interest the alumni of the program in the use of renewable energy in maritime engineering.

4 CONCLUSIONS

The UNM Solar Splash program was developed with the practical goal of competing against other college teams in the international intercollegiate solar-powered electric boat race, and with the aspiration to train future maritime engineers who can tackle the challenge of making global shipping more environmentally friendly and bringing it into compliance with the goals of the GHG emission reduction goals set by the Paris Climate Agreement.

Since 2016, we were able to recruit brilliant and strongly motivated seniors and graduate students. Among the distinguishing features of our program are close collaboration between two departments (Mechanical and Electrical and Computer Engineering), continuity provided by involvement both of senior level undergraduates and graduate students, and organization of the participants into multiple sub teams working on specific tasks and coordinating their efforts. Thanks to aggressive fundraising combined with outreach to the media and favourable coverage in the local news, the program is financially secure for at least another year. Our long-term fundraising goal is to receive funding sufficient for transitioning to an endowment model of support.

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