Técnico Solar Boat (TSB): Electrical Propulsion System Improvement Featuring a Dual Motor Drive

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Electrical and Computer Engineering

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15th June 2018
Dedicated to the entire Técnico Solar Boat team
Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.
Acknowledgements

I would like to thank first and foremost all of Técnico Solar Boat team. An extended gratitude to, in no particular order: João Silva for giving me the strength of joining this team with him two years ago and for his work as team leader. João Pinto for developing with me the controller hardware (and software) system for the dual motor drive - Alexandre Gonçalves for his work with the mechanical coupling of the dual motor. João Frazão for the various drag coefficients and the load profile of the propeller. Manuel Simas for his persistence in making all of this possible by finding partnerships with multiple companies. Sebastião Beirão for his immense dedication, making sure all our PCBs were done in time and for his excellent work in finding sponsorships. Tiago Miotto and Dinis Rodrigues for developing the cell discharger testbench which allowed me to get experimental data on the battery cells. Jonathan Graesser for his build ideas on the battery assembly and his proactive attitude. Last but not least, Basile Belime for succeeding me in the project.
Resumo

O objectivo principal desta tese consiste na modelação e por consequente melhoria da propulsão elétrica de um barco de competição movido a energia solar - a transmissão mecânica, o sistema de armazenamento de energia composto por baterias Litio-Polímero (LiPo), motor elétrico DC Brushless e o conjunto de painéis solares como fonte de energia do barco são todos considerados parte do sistema de propulsão.

As competições possuem regulamentos rigorosos. Para o sistema eléctrico existem limitações para a energia armazenada na bateria, assim como para a potência de pico produzida pelos painéis solares. Como todas as equipas concorrentes têm as mesmas restrições, será a equipa com o projecto mais eficiente que ganhará.

Os três principais tópicos abordados nesta tese são; o sistema de propulsão composto pelo acionamento electromecânico no motor do tipo DC Brushless (BLDC), o sistema de armazenamento de energia (baterias LiPo) e o sistema de produção de energia fotovoltaica (painéis solares). Todos estes sistemas serão modelados em termos de parâmetros concentrados e, onde possível, melhoramentos no seu desempenho serão estudados e implementados.

Para o sistema de propulsão elétrico do barco, propõe-se nesta tese um sistema com dois motores BLDC mecanicamente acoplados com controlo de torque, procurando-se uma solução com uma maior eficiência elétrica em relação ao sistema de propulsão anterior de apenas um motor BLDC com controlo de velocidade e não de torque.

Este sistema de duplo motor prova não mudar o desempenho do barco no endurance comparativamente a um motor e aumenta a velocidade de pico do barco em 66%.

Palavras-chave: Propulsão elétrica, energia fotovoltaica, armazenamento de energia, barco, controlo de torque.
Abstract

The main goal of this thesis is to model and consequently improve a solar powered boat propulsion system - the powertrain, the storage system composed of LiPo cells, BLDC motor and solar panels as a source of energy are all considered part of the propulsion system.

The competitions have strict regulations that the vessel must abide to. For the electrical system there limitations for the energy stored in the battery as well as power produced by the solar panels. Since teams have access to the same amount of energy, it is the team that has the most efficient project that will win.

The three main subjects that will be discussed in this thesis are: the propulsion system consisting of an electromechanical drive with a Brushless DC motor (BLDC), the energy storage system (LiPo batteries) and photovoltaic power production system (solar panels arrays). All these systems will be modelled in terms of lumped elements and improvements will be suggested and implemented wherever possible.

For the propulsion of the vessel, it is proposed in this thesis a system with two mechanically coupled motors with torque control, seeking a more efficient solution to the previous propulsion system composed by one motor with speed control.

The dual motor system performance is equal to the single motor for the endurance of the boat while increasing the vessel top speed by 66%.

Keywords: electrical propulsion, photovoltaic energy, energy storage, boat, torque control.
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Nomenclature

Greek symbols

\( \alpha \) Angular acceleration.
\( \delta \) Duty cycle.
\( \epsilon \) Error.
\( \eta \) Efficiency.
\( \omega \) Angular speed.
\( \rho \) Density.

Roman symbols

\( A \) Area.
\( a \) Acceleration.
\( c_d \) Drag coefficient.
\( I_0 \) Diode inverse saturation current.
\( V_T \) Diode thermal voltage.
\( E \) Energy.
\( F \) Force.
\( G \) Irradiance.
\( I \) Current.
\( J \) Propeller advance coefficient.
\( K \) Boltzmann constant.
\( k \) Gear ratio.
\( L \) Moment of inertia.
\( m \) Mass.
$N$ Rotational speed.

$P$ Power.

$q$ Electron charge.

$T$ Torque.

$t$ Time.

$T_{em}$ Electromagnetic torque.

$V$ Voltage.

$v$ Speed.

**Subscripts**

1, 2, 3 Indexes.

$a$ Ambient.

$eq$ Equivalent.

$i$ Computational index.

$n$ Nominal.

$oc$ Open circuit.

$p$ Peak.

$PP$ Pole pairs.

$pp$ Peak power.

$prop$ Propeller.

$sc$ Short circuit.

**Superscripts**

' Variant.

$r$ Reference.
## Glossary

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLDC</td>
<td>Brushless DC-motor is a synchronous permanent magnet motor with an electronic interface that, from DC voltage, sends controlled pulses to the motor coils.</td>
</tr>
<tr>
<td>BMS</td>
<td>Battery Management System is an electronic circuit that manages a battery pack by reading the various cell voltages and temperatures and protects the battery from operating outside its safe operating area.</td>
</tr>
<tr>
<td>C-rating</td>
<td>C-rating is a measure of battery current in relation to its capacity.</td>
</tr>
<tr>
<td>CAN</td>
<td>Controller Area Network is a robust bus standard that allows micro controllers and devices to communicate without a host computer.</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics is a branch of fluid mechanics that uses numerical methods and algorithms to solve problems that involve fluid flows.</td>
</tr>
<tr>
<td>DC-DC converter</td>
<td>DC-DC converter is an electronic circuit that converts direct current from one voltage level to another.</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform is a sampling algorithm that divides a signal into its frequency components.</td>
</tr>
<tr>
<td>Li-ion</td>
<td>Li-ion is a topology of rechargeable batteries where the electrolyte is composed of lithium ions.</td>
</tr>
<tr>
<td>LiPo</td>
<td>LiPo is a subcategory of Li-ion batteries where the electrolyte is made from a polymer instead of a liquid.</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
</tr>
<tr>
<td>---------</td>
<td>------------</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum Power Point Tracker is a internally controlled DC-DC converter with an algorithm to find and enforce a solar array voltage to its maximum power point.</td>
</tr>
<tr>
<td>MPP</td>
<td>Maximum Power Point is a voltage/current pair of a solar array which maximizes its power output.</td>
</tr>
<tr>
<td>NOCT</td>
<td>Normal Operating Cell Temperature is the nominal photovoltaic cell temperature under standard test conditions.</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board is a board with electrical connections that supports electrical components.</td>
</tr>
<tr>
<td>PID controller</td>
<td>PID controller is closed loop feedback system that has proportional, integrative and derivative feedback.</td>
</tr>
<tr>
<td>STC</td>
<td>Standard Test Conditions is the normalized conditions under which a photovoltaic cell is tested for its datasheet values.</td>
</tr>
<tr>
<td>SoC</td>
<td>State of Charge is the equivalent to a fuel gauge for a battery, it shows the remainder capacity of the cell.</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Motivation and topic overview

Since I got my driver’s license that I try to find new ways to reduce my fuel consumption. This led me to studying how my driving affected this consumption and the trade-offs of various driving methods. I bought an OBD-reader (On Board Diagnostics) which fed live information to my cellphone via bluetooth allowing me to regulate my driving and store information so I could analyse it at home by the means of an app - Torque Pro app (see figure 1.1).

Figure 1.1: Example of Torque Pro dashboard.

TSB’s project gave me the opportunity to work with energy management for electric mobility. Since the competitions regulate the energy stored and photovoltaic power production (area of photovoltaic cells), every team has an equal footing - the boat that wins the competition is therefore the one that used that energy the most efficiently.

As the motor is the greatest consumer in the electrical systems, a slight change in this system, efficiency-wise, reflects vastly in the power consumption of the boat. Since the competition is composed
of multiples races with distinctive drive cycles, there is a need to be efficient at low power regime (around 1.5 kW - endurance race) and being able to reach high power regime (around 10 kW - sprint race).

The vessel, named SR01, is made out of carbon fiber composite to be as lightweight as possible. SR01’s lightship is 79.4 kg and the total weight, including the skipper, battery box, propulsion column and various peripherals such as the fire extinguisher, amounts to 207 kg.

SR01 is equipped with hydrofoils: wings that are located underneath the water line (see figure 1.2). As the boat speeds up, they create lift to rise the hull from the water resulting in a reduced drag. This mechanical system impacts the propulsion of the boat as the drag changes drastically and will be taken into account for dimensioning the motor.

![Figure 1.2: SR01’s hull and hydrofoil system.](image)

Note in figure 1.2 the panels on each side of the hull. Their purpose is to support the photovoltaic cells. This year’s objective is to reduce the weight of the installed systems in order to achieve a sub 200 kg total weight while improving mechanical and electrical systems - the hull will remain unchanged. The battery pack and photovoltaic arrays also make up part of the electrical propulsion system. Therefore it is important to model them to identify the existing limitations in the powertrain while also detecting potential room for improvements.

## 1.2 State of the art

Currently there are multiple solar boats from various countries and universities in competition: nine in the ‘A class’ and twelve in the ‘top class’. These numbers are expected to rise as the competitions are fairly new and steadily growing. SR01 is an ‘A class’ type boat which limits the amount of solar panels and therefore was more economically viable as TSB’s first prototype. The competition rules contain regulations for the hull, the mechanical systems and electrical systems. Noteworthy rules for the electrical system are:

- Peak power production (photovoltaic cells) is limited to 1 kW;
- Energy storage is limited to 1.5 kWh;
• Maximum voltage allowed is 52 V;

• Batteries using lithium topology cells are limited to twelve cells in series.

The rules can be found in Appendix B. Note that there are no rules taking into account the motor - each team is free to choose its motor model and nominal power.

The previous iteration of SR01 did not feature hydrofoils and was equipped with a 4 kW BLDC motor located underwater at the propeller level (direct drive). The motor was an off-the-shelf outboard from Torqeedo and only had speed control. This prototype achieved a sprint speed of 24.3 km/h.

The battery was composed by Li-ion cells with cobalt cathode from GWL POWER. They were cylindrical ‘18650’ cells with a capacity of 2.6 Ah. Table 1.1 presents technical data of that cell.

<table>
<thead>
<tr>
<th>Nominal voltage [V]</th>
<th>3.70</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum voltage [V]</td>
<td>4.20</td>
</tr>
<tr>
<td>Minimum voltage [V]</td>
<td>2.75</td>
</tr>
<tr>
<td>Maximum continuous discharge current [C]</td>
<td>3C</td>
</tr>
<tr>
<td>Maximum temperature [°C]</td>
<td>60</td>
</tr>
<tr>
<td>Internal resistance [mΩ]</td>
<td>&lt;40</td>
</tr>
<tr>
<td>Cycle life</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>Weight [g]</td>
<td>&lt;48</td>
</tr>
</tbody>
</table>

Table 1.1: GWL POWER 2.6 Ah Li-ion cell specifications.

The current is given as C-rating, a measure of current relative to the capacity of the cell. The GWL POWER cell has a discharge of 3C which is equal to 7.8 A. To comply with the stored energy of 1.5 kWh, the battery had a cell configuration of 12S13P - meaning twelve cells in series and thirteen in parallel.

The battery specifications are shown in table 1.2 and its assembly in figure 1.3.

<table>
<thead>
<tr>
<th>Number of cells</th>
<th>156</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal voltage [V]</td>
<td>44.4</td>
</tr>
<tr>
<td>Maximum voltage [V]</td>
<td>50.4</td>
</tr>
<tr>
<td>Minimum voltage [V]</td>
<td>33</td>
</tr>
<tr>
<td>Capacity [Ah]</td>
<td>33.8</td>
</tr>
<tr>
<td>Energy [Wh]</td>
<td>1500.7</td>
</tr>
<tr>
<td>Maximum continuous discharge current [A]</td>
<td>101.4</td>
</tr>
<tr>
<td>Maximum temperature [°C]</td>
<td>60</td>
</tr>
<tr>
<td>Equivalent internal resistance [mΩ]</td>
<td>&lt;40</td>
</tr>
<tr>
<td>Weight (cells only) [kg]</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Table 1.2: SR01’s previous battery specifications.
Figure 1.3: SR01’s previous battery assembly.

Note that the cells have high energy density (200 Wh/kg) but low power density - the maximum continuous power is limited to 4500 W.

The photovoltaic array is composed by multiple flexible monocrystalline silicon solar panels with a peak power of 1000 W. The solar panels from the last year will be reused, partially due to their high price and the lack of adequate panels with higher efficiencies. Their description will follow in chapter 2.

Of the nine teams present in the ‘A class’, only one team has implemented hydrofoils, NHL Solar-boatteam. All the teams except two have flexible monocrystalline silicon solar panels - the other two have rigid and heavier panels. It is speculated, from exchanged words with the teams, that all of them use MPPTs (Maximum Power Point Tracker) in order to receive a higher solar panel power output.

In the top three teams (based on last year’s results), there are two teams with LiPo pouch cells and one with Li-ion Cobalt cylindrical cells. Moreover, the three teams all have BLDC motors with L-drives (see figure 1.4), meaning their motors are outside the water - this grants them a much more streamlined underwater column and thus less drag from their propulsion column.

Figure 1.4: Example of an L-drive where the motor is out of the water.

For the top class teams, two have implemented foils. CLAFIS, a private team, has a three foil system in a ‘T’-configuration - two near the bow and one at the stern. The front foils have their angle of attack controlled mechanically by skates that float on the water (figure 1.5).
TU Delft Solar Boat Team has a four foil system - two at the bow and two at the stern. Delft’s front and rear foils can change the angle of attack and they are controlled electronically. TU Delft controls their foils by the means of sensors and a PID controller (figure 1.6).

Figure 1.5: CLAFIS solar boat with mechanical control on the foils (skates measure distance to the water).

Figure 1.6: TU Delft solar boat with a ultrasonic distance sensor (at the bow).

1.3 Objectives

One of the goals set by the TSB team is to have a better sprint in 2018, which means more a more powerful propulsion system or less drag. We will address both by implementing foils and a more powerful motor setup. In this context, the primary objective of this thesis is to implement the new electric propulsion system, increasing the performance of the vessel for both endurance and sprint race. The new propulsion system is composed by two mechanically coupled motors. Therefore one of the objectives of this thesis is to confirm that such a system works as intended and has enough fidelity to be featured in the vessel of 2018.

This thesis also serves as a future guide for further improvements of SR01’s electrical systems and is built upon a thesis by Francisco Duarte [1], the previous electrical systems leader of TSB.

1.4 Thesis outline

In order to dimension a traction motor, one must first compute the expected power input of the motor. The photovoltaic power production system will be studied in order to estimate the instantaneous and average power output under different weather cases such as varying ambient temperature and the sun’s irradiation. This model will be verified by experimental data.
A new battery that is lighter and capable of higher current discharges will be analysed and assembled. The choice of battery cell is studied in order to make an informed decision. Experimental data will be acquired to verify the cooling of the battery.

The mechanical equation of the boat will be expressed and the choice of hydrofoils will be justified through theoretical calculations. The drag of the vessel and hydrofoils is used to find the power output needed from the powertrain.

The propulsion system will be completely re-evaluated. The new system will consist of two BLDC motors with an L-drive propeller configuration. The electromechanical power conversion efficiency will be studied and a means to torque control both motors in order to make them as efficient as possible will be developed.

SR01’s performance will be studied for multiple drive cycles that the vessel will encounter during the competitions, comparing the proposed new solution proposed against a single motor solution.
Chapter 2

Solar Power Generation System

2.1 Theoretical model

The solar panels used are the Solbian SP series that feature monocrystalline silicon cells (see datasheet in Appendix B). The specifications are indicated in table 2.1 for standard test conditions ($G^r = 1000 \text{ W/m}^2$ $T_{cell} = 25 \degree \text{C}$).

<table>
<thead>
<tr>
<th>Efficiency $\eta$ [%]</th>
<th>20.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak power $P_p$ [W]</td>
<td>3.26</td>
</tr>
<tr>
<td>Power drop due to temperature [%/\degree \text{C}]</td>
<td>-0.32</td>
</tr>
<tr>
<td>Voltage drop due to temperature [mV/\degree \text{C}]</td>
<td>-1.80</td>
</tr>
<tr>
<td>Open circuit voltage $V_{oc}$ [V]</td>
<td>0.68</td>
</tr>
<tr>
<td>Peak power voltage $V_{pp}$ [V]</td>
<td>0.55</td>
</tr>
<tr>
<td>Short circuit current $I_{sc}$ [A]</td>
<td>6.29</td>
</tr>
<tr>
<td>Peak power current $I_{pp}$ [A]</td>
<td>5.92</td>
</tr>
<tr>
<td>Normal operating cell temperature NOCT [\degree \text{C}]</td>
<td>45</td>
</tr>
<tr>
<td>Area [m$^2$]</td>
<td>0.0156</td>
</tr>
<tr>
<td>Weight [kg]</td>
<td>0.044</td>
</tr>
</tbody>
</table>

Table 2.1: Solbian SunPower cell specifications.

Note that in table 2.1 the efficiency, $\eta$, is given by

$$\eta = \frac{P_p}{A \cdot G^r}, \quad (2.1)$$

with $A$ being the solar cell area and $G^r$ the standard test irradiance. The weight, in table 2.1, is measured by averaging the various solar panels bought from Solbian divided by their number of cells. The full weights and cell number of each panel are shown in table 2.2.

<table>
<thead>
<tr>
<th>Panel</th>
<th>Number of cells</th>
<th>Weight [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>42</td>
<td>1.85</td>
</tr>
<tr>
<td>B</td>
<td>48</td>
<td>2.10</td>
</tr>
<tr>
<td>C</td>
<td>32</td>
<td>1.42</td>
</tr>
<tr>
<td>D</td>
<td>38</td>
<td>1.69</td>
</tr>
</tbody>
</table>

Table 2.2: SR01 photovoltaic panels weight.
The model used for the photovoltaic cell is the single diode equivalent [2] shown in figure 2.5.

\[ I_D = I_0 \left( e^{\frac{V}{mVT}} - 1 \right) \]  

(2.2)

where \( I_0 \) is the inverse saturation current, \( m \) is the diode ideality factor and \( V_T \) is the thermal voltage given by

\[ V_T = \frac{KT}{q} \]  

(2.3)

Applying Kirchhoff’s current law to the schematic shown in figure 2.5 we obtain
\[ I = I_{sc} - I_D = I_{sc} - I_0 \left( e^{\frac{V}{mV_T}} - 1 \right). \] (2.4)

It is possible from the datasheet values presented in table 2.1 to compute the photovoltaic cell parameters that will allow to simulate it under different conditions such as higher ambient temperature or lower irradiation.

The diode ideality factor is a constant that can be obtained by the datasheet values. From that it is possible to obtain the inverse saturation current for the STC.

\[ m = \frac{V_{pp} - V_{oc}}{V_T \cdot \ln \left( 1 - \frac{I_{pp}}{I_{sc}} \right)} \] (2.5)

\[ I_0' = \frac{I_{sc}}{e^{\frac{V_{sc}}{mV_T}} - 1} \] (2.6)

Taking the equations (2.6) and (2.4) while considering \( e^{\frac{V_{sc}}{mV_T}} \gg 1 \) and \( e^{\frac{V}{mV_T}} \gg 1 \), we can simplify the photovoltaic cell current equation to

\[ I = I_{sc} - \frac{I_{sc}}{e^{\frac{V}{mV_T}}} \left( e^{\frac{V}{mV_T}} \right) \rightarrow I \simeq I_{sc} \left( 1 - e^{\frac{V - V_{oc}}{mV_T}} \right). \] (2.7)

To justify this simplification, one can compute \( e^{\frac{V_{sc}}{mV_T}} \) from the datasheet values and \( e^{\frac{V}{mV_T}} \) using STC values which yields

\[
\begin{align*}
e^{\frac{V_{sc}}{mV_T}} &= 2.68 \cdot 10^6 \gg 1 \\
e^{\frac{V}{mV_T}} &= 1.58 \cdot 10^5 \gg 1
\end{align*}
\]

thus validating the simplification. Now that we described the cell current as a function of its voltage, it is possible to draw the power curve as shown in figure 2.6.
Note that for STC the photovoltaic cell outputs a peak power of 3.26 W at 0.56 V as expected from the datasheet. It is now possible to compute the power output and peak power voltage for conditions other than the standard test.

The cell temperature can be computed from the ambient temperature by

$$T_c = T_a + G \cdot \frac{NOCT - 20}{800}$$  \hspace{1cm} (2.8)

where NOCT is the normal operating cell temperature given in the datasheet.

The change in temperature will influence the thermal voltage $V_T$ (equation (2.3)) and the diode inverse saturation current

$$I_0 = DT^3 e^{-\frac{I}{mV_T}}.$$  \hspace{1cm} (2.9)

Note that $D$ is a constant that is not relevant since we know the $I_0$ for the standard test conditions - $I_0$. This gives

$$I_0 = I_0' \left( \frac{T}{T_0} \right)^{\frac{1}{n}} \left( \frac{V_T}{V_T} \right)^{\frac{1}{n}}.$$  \hspace{1cm} (2.10)

These parameters will influence the open circuit voltage which can be deduced from the current equation (2.4) using $I = 0$ (open circuit) which yields

$$0 = I_{sc} - I_0 \left( e^{\frac{V_{oc}}{mV_T}} - 1 \right) \Longrightarrow V_{oc} = mV_T \ln \left( 1 + \frac{I_{sc}}{I_0} \right)$$  \hspace{1cm} (2.11)
The radiation $G$ influences the temperature as seen in equation (2.8) but also influences the short-circuit current

$$I_{sc} = I_{sc}^r \frac{G}{G^r}.$$  \hspace{1cm} (2.12)

It is now possible to show the influence of the irradiance and temperature on the power output and peak power voltage of a photovoltaic cell.

Figures 2.7 and 2.8 display the role of the irradiance on the voltage and current of a photovoltaic cell and the resulting power changes. The temperature is constant and equal to $25\, ^\circ C$.

![Figure 2.7: Photovoltaic cell V-I curve with varying irradiance.](image)

![Figure 2.8: Photovoltaic cell V-P curve with varying irradiance.](image)

Note that the irradiance has a large influence on the short circuit current but almost none on the open circuit voltage. The figure 2.8 shows that the peak power changes but the peak power voltage stays approximately the same. The values obtained for those two parameters are shown in table 2.3.
Now keeping the irradiation constant and equal to the standard condition, $G = 1000 \text{ W/m}^2$, we will change the cell temperature and study its influence on the power output of a photovoltaic cell.

Figures 2.9 and 2.10 present the influence of the temperature on the photovoltaic cell power output.

Note, from figure 2.9, that the temperature only influences the open circuit voltage. Therefore, the temperature has a significant influence on the peak power voltage (see table 2.4).

### Table 2.3: Peak power and peak power voltage for different irradiations.

<table>
<thead>
<tr>
<th>$G$ [W/m$^2$]</th>
<th>$V_{pp}$ [V]</th>
<th>$P_p$ [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>0.50</td>
<td>0.57</td>
</tr>
<tr>
<td>400</td>
<td>0.52</td>
<td>1.21</td>
</tr>
<tr>
<td>600</td>
<td>0.54</td>
<td>1.88</td>
</tr>
<tr>
<td>800</td>
<td>0.55</td>
<td>2.57</td>
</tr>
<tr>
<td>1000</td>
<td>0.56</td>
<td>3.26</td>
</tr>
</tbody>
</table>
Table 2.4: Peak power and peak power voltage for different cell temperatures.

<table>
<thead>
<tr>
<th>$T$ [°C]</th>
<th>$V_{pp}$ [V]</th>
<th>$P_{pp}$ [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0.56</td>
<td>3.26</td>
</tr>
<tr>
<td>35</td>
<td>0.54</td>
<td>3.14</td>
</tr>
<tr>
<td>45</td>
<td>0.52</td>
<td>3.00</td>
</tr>
<tr>
<td>55</td>
<td>0.50</td>
<td>2.87</td>
</tr>
<tr>
<td>65</td>
<td>0.48</td>
<td>2.73</td>
</tr>
</tbody>
</table>

2.2 SR01’s photovoltaic arrays

The regulation of the competition limited the peak photovoltaic power production to 1 kW. Using the SunPower cells, we can obtain that power with 320 photovoltaic cells which occupy $5 \text{ m}^2$.

Figure 2.11 shows the geometric configuration of the solar cells of each panel, as well as the distribution of the photovoltaic panels on the boat. Note that each panel listed previously in table 2.2 is duplicated.

![Figure 2.11: Shapes of the solar panels and distribution on the boat.](image)

The solar cells are oriented at zero degrees in reference with the earth and do not feature any concentrators. These two conditions are featured in the competition regulation.

Every photovoltaic panel has its cells interconnected in series. The panels A, B, C and D are also interconnected in series in the following manner:

- A and D $\rightarrow$ 42+32=80 cells in series;
- B and C $\rightarrow$ 48+32=80 cells in series.

Thus there are four arrays each composed by 80 cells in series. The idea behind having four equal arrays is to, in the future, build our own MPPT in which all the arrays connect in parallel.

Using the electrical specifications given by Solbian (see table 2.1), it is possible to compute the specifications of each array, as shown in table 2.5 for STC.
Table 2.5: SR01’s photovoltaic array (80 cells in series) electrical specifications.

As for the expected power output during the current competition, one can analyse the last year’s competition. The ambient temperature was about 26 °C and the mean irradiation 670 W/m² for the morning of 14th of July [3]. These parameters allow us to compute the mean power produced from SR01’s photovoltaic cells, as well as the peak power voltage of each array and their respective current. All values are given in the table 2.6.

Table 2.6: SR01’s photovoltaic array power output for the endurance race ($G = 670\text{ W/m}^2$, $T_a = 26\text{ °C}$).

2.2.1 Update on the solar panels

Since the start of this thesis, the regulation has changed to restrict the maximum area of solar cells to 6 m². For our cells, this means that the new peak power output can be increased by 20% to 1200 W.

The new cells are all featured into a new, single panels of 64 cells in series (see figure 2.12) with its own MPPT, equal to the MPPT used in the other four arrays. The power output of the global solar array is therefore increased by 20% - the new value is 736.6 W.

Figure 2.12: SR01 new solar panel (surrounded by a black box) featured in the stern of the boat.
2.3 SR01’s maximum power point trackers

A MPPT is a DC-DC converter with variable duty cycle thus it possesses a variable voltage gain or reduction. Since the output voltage is the battery voltage (static), it was used as a reference. Changing the DC-DC conversion rate only impacts the solar array voltage, which behaves like a current source (non static voltage).

![MPPT diagram]

Figure 2.13: MPPT input and output ports.

In SR01’s case, the battery nominal voltage, 44.4 V, is higher than the typical peak power voltage of its arrays, 44.0 V at STC, meaning an even lower voltage for higher temperatures.

A controlled boost converter [4] is the ideal MPPT in this case, with

\[ V_{\text{panel}} = (1 - \delta)V_{\text{battery}}, \]  

\( (2.13) \)

with \( \delta \) being the duty cycle of the converter ranging from zero to one. This duty cycle is controlled by a microprocessor which sweeps the various voltages to find the one which yields the most power output, the maximum power point.

Section 2.1 described that the vessel features four identical photovoltaic arrays of 80 cells in series. The simplest solution would be to have one MPPT for the four arrays and connect them in parallel since they are electrically identical - the \( V_{pp} \) is the same for all the arrays assuming similar temperature and radiation, which is plausible given the boat small area.

The solution of a single MPPT demands a converter that can handle a current of 23.7 A (four arrays in parallel each with \( I_{pp} = 5.9 \) A). Unfortunately there are little options of MPPTs of low voltage that handle such current. The TSB team managed to find a sponsor with Genasun that manufactures boost MPPTs for our voltage range (see datasheet in Appendix B).
Note that the MPPT is a custom solution for SR01’s battery which has a nominal voltage of 44.4 V and a absorption voltage (fully charged voltage) of 50.4 V. Table 2.7 offers an overview on the MPPT specifications.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum input voltage [V]</td>
<td>60</td>
</tr>
<tr>
<td>Maximum input current [A]</td>
<td>8</td>
</tr>
<tr>
<td>Nominal battery voltage [V]</td>
<td>44.4</td>
</tr>
<tr>
<td>Battery absorption voltage [V]</td>
<td>50.4</td>
</tr>
<tr>
<td>Weight [g]</td>
<td>185</td>
</tr>
</tbody>
</table>

Table 2.7: SR01’s MPPT specifications.

The final solution is a MPPT for every array since each MPPT only handles 8 A. This solution gives us a total of four MPPT as seen in figure 2.15.
2.4 Partial shading of the arrays

As explained in Section 2.2 the photovoltaic cell output depends on the irradiance it receives. SR01’s solar panels are made with the photovoltaic cells interconnected in series. Thus, if one or multiple cells perceive less irradiation such as a localized shadow, it will impact the performance of the entire array. Figure 2.16 shows an example of an array with three cells in series that are exposed to differing irradiations.

Let us assume equal temperatures on all cells and $G_1 > G_2 > G_3$. The $V_{pp}$ of the three cells is almost equal but the current output is limited to ‘cell 3’ since it has the lowest irradiation (see figure 2.7). Therefore, the power output is limited by the cell with the lowest irradiation, which limits the output current of the solar array. Taking into account $G_1 = 600 \text{ W/m}^2$ and $G_3 = 200 \text{ W/m}^2$ the cells’ currents, at
peak power voltage, are

\[
\begin{align*}
I_1 &= 3.5 \text{ A}, \\
I_3 &= 1.0 \text{ A}.
\end{align*}
\]

Cell 1 is capable of delivering 3.5 A but is limited by cell 3 current, which is the array current. If by any chance a cell is fully obstructed, the entire array will be in open and no power will flow from it.

Fortunately, the solar panels are equipped with bypass diodes to address this issue. A bypass diode allows the current to bypass a photovoltaic cell if it is not producing energy [5]. This is an important feature since, when a cell is fully shaded but there is current flowing (from the other cells in series), the cell will actually consume power and heat up, potentially burning or damaging the photovoltaic panel.

![Figure 2.17: Bypass diodes on solar panel 'D'.](image)

Note that, in figure 2.17, there isn’t a bypass diode per cell but rather per every two row of cells. Such arrangements are common since equipping each cell with a bypass diode proves to be costly. It is possible to observe, in figure 2.18, the bypass diodes in the panel ‘A’.

![Figure 2.18: SR01’s panel ‘A’ bypass diodes with respective cell regions.](image)
Note that in figure 2.18 the bypass diode’s cells are marked with the same colour as the diode. In order to better understand the connections figure 2.19 presents the electrical scheme of the panel 'A'.

![Figure 2.19: Panel 'A' electrical scheme.](image)

The array is composed by three groups of fourteen photovoltaic cells. If a cell is fully shaded, instead of opening the whole solar array only the cells grouped with the shaded cell are bypassed, resulting in a solar panel with less cells in series thus a reduced voltage (see figure 2.21).

![Figure 2.20: Panel 'A' with one shaded cell - the bottom bypass diode is conducting.](image)
It is also interesting to consider a case where the shaded cell isn’t fully shaded but with reduced irradiance. Having less irradiance means that the cell will not be able to output as much current as the rest of the cells. Let us consider, for example, that all the cells are uniformly irradiated with $G = 1000 \text{ W/m}^2$ and one cell (the same as in figure 2.21) has a reduced irradiance of $G' = 200 \text{ W/m}^2$. Assuming standard cell temperature ($T_{cell} = 25^\circ\text{C}$), it is possible to compute the maximum current for the normal cells and the shaded cell:

\[
\begin{align*}
I_G &= 6.1 \text{ A}, \\
I_{G'} &= 1.2 \text{ A}.
\end{align*}
\]

Therefore, the group of cells containing the slightly shaded cell will be bypassed if the current drawn from the solar panel is superior to its maximum current, as seen in figure 2.22.
The voltage drop seen in figure 2.22 happens when the bypass diode starts conducting, effectively removing fourteen cells from the array. The power of the array, with the slightly shaded cell, is given in figure 2.23.

![Figure 2.23: Panel 'A' I-P curve with a slightly shaded cell.](image)

Note that there is a local maximum - gladly the MPPT that was acquired overcomes this problem and searches for the real maximum power point instead of staying on the local maxima caused by partial shading. Therefore the partial shading problem is fixed thanks to the bypass diodes present in the solar panels as well as the functionality of the MPPT which is ready for such situations.

Partial shading power losses are not considered in the total power available for the motor since the occurrence of this event is unknown to the team as for now. This year the solar arrays’ voltage will be monitored in order to know how often cells are bypassed, thus developing a model that allows to take partial shading into account.

### 2.5 Experimental data

#### 2.5.1 Experimental V-I curves

In order to confirm the single diode equivalent model of the solar cells, panel 'A' was tested, as seen in figure 2.24.
This test includes connecting the solar photovoltaic panel to a variable resistor in order to obtain multiple voltage and current readings. The resistor is variable between 0 and 55 Ω but its maximum current rating is 5 A. Due to this load limitation, the open circuit voltage $V_{oc}$ is measured with the load disconnected and the short circuit current $I_{sc}$ is measured by shorting the panel plus and minus directly.

The irradiance is obtained through a pyranometer (see figure 2.24), RS Pro ISM400. The current is obtained by the means of a current clamp.

Since the tests were performed in outdoors, there is no control over the irradiance: the results shown are given for a certain resolution, i.e.: between 600 W/m² and 650 W/m². The measurements were made after allowing the panel reach its steady state temperature.

Three different irradiance tests were performed:

1. [400; 450] W/m², $T_a = 20$ °C and $T_c = 35.0$ °C;
2. [600; 650] W/m², $T_a = 21$ °C and $T_c = 42.5$ °C;
3. [850; 900] W/m², $T_a = 25$ °C and $T_c = 54.5$ °C.

The data acquired is resumed in table 2.8.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>25.7 ± 0.1</td>
<td>0.0</td>
<td>25.8 ± 0.1</td>
<td>0.0</td>
<td>26.1 ± 0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>25.5 ± 0.1</td>
<td>0.8 ± 0.1</td>
<td>25.4 ± 0.1</td>
<td>0.5 ± 0.1</td>
<td>25.1 ± 0.1</td>
<td>1.1 ± 0.1</td>
</tr>
<tr>
<td>24.5 ± 0.1</td>
<td>1.4 ± 0.1</td>
<td>25.3 ± 0.1</td>
<td>1.2 ± 0.1</td>
<td>25.0 ± 0.1</td>
<td>1.7 ± 0.1</td>
</tr>
<tr>
<td>24.1 ± 0.1</td>
<td>1.8 ± 0.1</td>
<td>24.2 ± 0.1</td>
<td>2.6 ± 0.1</td>
<td>24.7 ± 0.1</td>
<td>2.9 ± 0.1</td>
</tr>
<tr>
<td>20.6 ± 0.1</td>
<td>2.5 ± 0.1</td>
<td>21.8 ± 0.1</td>
<td>3.5 ± 0.1</td>
<td>23.5 ± 0.1</td>
<td>3.5 ± 0.1</td>
</tr>
<tr>
<td>15.2 ± 0.1</td>
<td>2.6 ± 0.1</td>
<td>15.5 ± 0.1</td>
<td>3.9 ± 0.1</td>
<td>22.3 ± 0.1</td>
<td>4.6 ± 0.1</td>
</tr>
<tr>
<td>10.0 ± 0.1</td>
<td>2.7 ± 0.1</td>
<td>10.2 ± 0.1</td>
<td>3.9 ± 0.1</td>
<td>21.1 ± 0.1</td>
<td>4.9 ± 0.1</td>
</tr>
<tr>
<td>0.0</td>
<td>2.8 ± 0.1</td>
<td>0.0</td>
<td>4.0 ± 0.1</td>
<td>0.0</td>
<td>5.5 ± 0.1</td>
</tr>
</tbody>
</table>

Table 2.8: Experimental voltage and current values obtained from solar panel 'A'.
Figure 2.25 shows the experimental curves obtained with the model reference curves.

Figure 2.25: Experimental values (circles) compared to model values (dashed lines).

It is possible to visualize that the model values are consistent with the experimental data acquired. Note that the experimental open circuit voltage is below the expected values of the model. Since the rest of the curve is coinciding with the experimental values, the real temperature of the cells are likely to be higher than the model prediction - this would explain the voltage drop. Therefore the next subsection will verify the temperature model.

2.5.2 Thermal test

The model used to compute the photovoltaic cell temperature, seen in equation (2.8), is a function of the ambient temperature and irradiance.

The temperature reading was done by a thermal camera (PCE-TC 28) with an accuracy of 2 °C. Table 2.9 resumes the experimental values obtained and compares them with the model used. Note that these tests were performed after the tests in Subsection 2.5.1 in order for the panel to reach its steady state temperature.
<table>
<thead>
<tr>
<th>$T_e$ [°C]</th>
<th>Irradiance [W/m²]</th>
<th>Model $T_c$ [°C]</th>
<th>Measured $T_c$ [°C]</th>
<th>ε [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>425±25</td>
<td>33.3±1</td>
<td>35.0±2</td>
<td>+5.0</td>
</tr>
<tr>
<td>21</td>
<td>625±25</td>
<td>40.5±1</td>
<td>42.5±2</td>
<td>+4.9</td>
</tr>
<tr>
<td>25</td>
<td>875±25</td>
<td>52.4±1</td>
<td>54.5±2</td>
<td>+4.0</td>
</tr>
</tbody>
</table>

Table 2.9: Experimental temperatures compared to the model temperatures.

It is possible to observe that the temperatures recorded are about 5% higher than the model prediction. In these tests, the panel was stationary. However, during the competition the panels will have air flowing on top of them as well as water sprinkling - therefore the panel temperature should be below the recorded values in table 2.9. Thus it is safe to say that the model developed in this section is confirmed and yields good results.

### 2.5.3 Non uniform irradiance test

In order to verify the bypass diode functionality, a test was carried with a solar panel - panel 'A'.

![Photovoltaic panel 'A' irradiated non uniformly.](image)

The test was performed in a laboratory with four lamps as seen in figure 2.26. The output of the solar panel was connected to a variable resistance, which allowed to change to photovoltaic array voltage. The temperature of the solar panel was also measured by the means of a thermistor (NTCLE413).

The mean irradiance was measured for each group of cells connected to a bypass diode, yielding the values shown in table 2.10.
The irradiances shown in table 2.10 were obtained with a pyranometer, RS Pro ISM400. The experimental current-voltage curve is shown in figure 2.28. During the test, the thermistor value changed from 7.19 kΩ to 6.50 kΩ meaning the cells’ temperature fluctuated between (32.26 ± 1.00) °C and (33.87 ± 1.00) °C.

It is possible to observe in figure 2.28 a voltage drop from 24 V to 8 V around a current of 1.1 A. This is due to the two bypass diodes, responsible for the cells in group ‘A’ and ‘C’, starting conducting since those two areas had reduced irradiance. In fact, after the voltage drop, the voltage level is exactly one third of the normal voltage meaning that two thirds of the cells are bypassed. The theoretical model shows that for cells irradiated with 200 W/m² the maximum current is 1.2 A which is consistent with the
experimental results obtained.
Chapter 3

Energy Storage

3.1 Battery dimensioning

The battery model used in this thesis is the simple voltage source with a resistance in series.

![Battery cell concentrated parameters model.](image)

There are two constrains given by the competition, already stated in section 1.2, that will define the battery:

1. Batteries using lithium topology cells are limited to twelve cells in series;

2. Energy storage is limited to $1.5 \text{kWh}$.

The battery is expected to output at least $10 \text{kW}$ of peak power for the sprint race and around $2 \text{kW}$ of continuous power for the endurance race. Even at the allowed maximum voltage of $52 \text{V}$ those powers translate into high currents: $192 \text{A}$ for the peak power and $38 \text{A}$ for continuous power. This limits the choice of possible cells to high current drain ones.

In order to reduce power losses through Joule effect, we will choose the maximum number of cells in series so that the power transmission inside the boat is done at the highest possible voltage. Therefore the battery pack will feature twelve cells in series.

Lithium cells voltage depends on their state of charge (SoC) as seen in figure 3.2.
The nominal voltage, $V_n$, of a lithium topology cell is 3.7 V - thus our battery will have a nominal voltage of 44.4 V. Since the energy stored in a battery is given by

$$E = V_n \cdot C,$$

the desired battery capacity is deduced as

$$C = \frac{E}{V_n} = \frac{1500}{44.4} = 33.78 \text{ Ah}. \quad (3.2)$$

Table 3.1 resumes the specifications of the battery.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery energy [Wh]</td>
<td>1500</td>
</tr>
<tr>
<td>Topology</td>
<td>Lithium</td>
</tr>
<tr>
<td>Cell nominal voltage [V]</td>
<td>3.7</td>
</tr>
<tr>
<td>Cell maximum voltage [V]</td>
<td>4.2</td>
</tr>
<tr>
<td>Cell minimum voltage [V]</td>
<td>3.0</td>
</tr>
<tr>
<td>Cells in series</td>
<td>12</td>
</tr>
<tr>
<td>Battery maximum voltage [V]</td>
<td>50.4</td>
</tr>
<tr>
<td>Battery nominal voltage [V]</td>
<td>44.4</td>
</tr>
<tr>
<td>Battery capacity [Ah]</td>
<td>33.78</td>
</tr>
</tbody>
</table>

Table 3.1: SR01’s battery project specifications.

In order to reach the dimensioned battery capacity, multiple cells in parallel with lesser capacity are employed. Table 3.2 presents the possible capacities and number of parallel cells pair to reach the goal of storing 1.5 kWh.
The regulation penalizes the teams that have more than 1500 Wh. Therefore, cells that give an assembly with energy stored greater than 1500 Wh are disfavored. On the other hand, cells with higher capacity are favored since the assembly is simpler: there are less cells overall.

Note that the cell chosen must be capable of delivering the peak power needed. At nominal voltage, 44.4 V the current pulled for 10 kW is 225 A. Table 3.3 shows the current output needed for a given model.

<table>
<thead>
<tr>
<th>Capacity [Ah]</th>
<th>( N_{parallel} )</th>
<th>Current per parallel [A]</th>
<th>Minimum C-rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.6</td>
<td>13</td>
<td>17.3</td>
<td>7</td>
</tr>
<tr>
<td>2.8</td>
<td>12</td>
<td>18.8</td>
<td>7</td>
</tr>
<tr>
<td>3.7</td>
<td>9</td>
<td>25</td>
<td>7</td>
</tr>
<tr>
<td>3.8</td>
<td>9</td>
<td>25</td>
<td>7</td>
</tr>
<tr>
<td>4.2</td>
<td>8</td>
<td>28.1</td>
<td>7</td>
</tr>
<tr>
<td>4.8</td>
<td>7</td>
<td>32.1</td>
<td>7</td>
</tr>
<tr>
<td>5.6</td>
<td>6</td>
<td>37.5</td>
<td>7</td>
</tr>
<tr>
<td>6.8</td>
<td>5</td>
<td>45</td>
<td>7</td>
</tr>
<tr>
<td>8.4</td>
<td>4</td>
<td>56.3</td>
<td>7</td>
</tr>
<tr>
<td>16.8</td>
<td>2</td>
<td>112.5</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 3.3: C-rating.

The minimum C-rating required, for any model, is 7C. But for different capacity cells we have higher or lower currents per cell that will influence the section of the serial connection of the cells.

In order to judge between similar cases two figures of merit are important:

1. Energy density [Wh/kg] - higher numbers ensure our battery is lighter;

2. Internal resistance [\(\Omega\)] - lower numbers helps with the Joule losses and keeps the cooling system smaller (and having a low power consumption).

These figures were taken from a cell’s datasheet, therefore the next section will present the choices that are available.

### 3.2 SR01’s cell choice

Current advances in lithium cell technology highlight two cell types:
1. Cylindrical cells, typically cobalt cathode;

2. Pouches, typically polymer cells.

Cylindrical cells come in many dimensions. Previously the industry standard was the ‘18650’ (18 mm in diameter and 65 mm of height) but cell manufacturers are now relying on bigger cells such as the ‘20700’ and ‘21700’. Table 3.4 resumes the models that are pertinent for our case.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>NCR20700A</td>
<td>20700</td>
<td>3.2</td>
<td>60</td>
<td>197</td>
<td>10C</td>
<td>-</td>
<td>10</td>
<td>1421</td>
</tr>
<tr>
<td>NCR20700B</td>
<td>20700</td>
<td>4.2</td>
<td>70</td>
<td>222</td>
<td>3C</td>
<td>5C</td>
<td>8</td>
<td>1492</td>
</tr>
<tr>
<td>iJoy</td>
<td>21700</td>
<td>4.8</td>
<td>63</td>
<td>220</td>
<td>6C</td>
<td>11C</td>
<td>9</td>
<td>1499</td>
</tr>
<tr>
<td>INR 48G</td>
<td>21700</td>
<td>3.0</td>
<td>69</td>
<td>161</td>
<td>2C</td>
<td>7C</td>
<td>7</td>
<td>1492</td>
</tr>
<tr>
<td>INR 30T</td>
<td>21700</td>
<td>2.6650</td>
<td>92</td>
<td>169</td>
<td>5C</td>
<td>12C</td>
<td>8</td>
<td>1492</td>
</tr>
<tr>
<td>EFest IMR</td>
<td>26650</td>
<td>4.2</td>
<td>69</td>
<td>169</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.4: Cylindrical cells specifications.

Unfortunately, the cylindrical cells datasheets are lacking internal resistance value but there are many community reviews on these type of cells. The NCR20700B and iJoy are of interest since their capacity allows for a stored energy close to the limit of 1.5 kWh and they have the highest energy density of commercial cells - our battery would weight around 6.7 kg (cells only) which is already an improvement from last year’s 7.5 kg.

As for pouches, TSB team found a company, Melasta, that provided complete datasheet on all their models in a very detailed way.

![Figure 3.3: 4.2 Ah Melasta cells.](image)

Note in figure 3.3 that the cell capacity is a drop down menu with over 50 different capacities, each with multiple cell models. Therefore only the most interesting models were picked - table 3.5 resumes the three best models.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4.8</td>
<td>202</td>
<td>5C</td>
<td>8C</td>
<td>7</td>
<td>1492</td>
<td>3.5</td>
</tr>
<tr>
<td>5.6</td>
<td>223</td>
<td>5C</td>
<td>8C</td>
<td>6</td>
<td>1492</td>
<td>3.5</td>
</tr>
<tr>
<td>16.8</td>
<td>202</td>
<td>10C</td>
<td>15C</td>
<td>2</td>
<td>1492</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 3.5: Melasta LiPo cells specifications.

Despite the constant current below 7C of the cells of lesser capacity, they are still considered since they can output a pulse current of 8C. 7C is a worst case scenario discharge of the battery in which the motor is requesting maximum power, 10 kW, and the solar panels aren’t outputting power.

As for the cells’ resistance, it is possible to observe a lower value for the bigger capacity cell, the 16.8 Ah. But the figure of merit is the equivalent circuit resistance since different capacity cells have different currents running through them.

- Seven 4.8 Ah with internal resistance of 3.5 mΩ \(\rightarrow R_{eq} = 0.5 \text{ mΩ} \);
- Six 5.6 Ah with internal resistance of 3.5 mΩ \(\rightarrow R_{eq} = 0.58 \text{ mΩ} \);
- Two 16.8 Ah with internal resistance of 1.2 mΩ \(\rightarrow R_{eq} = 0.6 \text{ mΩ} \).

The equivalent internal resistance of the three assemblies is very similar thus this figure of merit will not influence the cell choice.

As the final decision, LiPo pouches are chosen as they are easier to assemble and connect electrically over their tabs. The fact that Melasta offered complete datasheets on their products and a discount on the purchase favoured their cells over other LiPo cell providers and other cylindrical cell choices.

The chosen cell is the LiPo 16.8 Ah (see figure 3.4) for it greatly increases the simplicity of the assembly seeing that there is no need of bus bars to do parallel connections as shown in the following section.

Figure 3.4: 16.8 Ah LiPo pouch cell.
### 3.3 SR01’s battery assembly

Table 3.6 resumes the cell specifications.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal voltage [V]</td>
<td>3.7</td>
</tr>
<tr>
<td>Maximum voltage [V]</td>
<td>4.2</td>
</tr>
<tr>
<td>Minimum voltage [V]</td>
<td>3.0</td>
</tr>
<tr>
<td>Maximum continuous discharge current [C]</td>
<td>10C</td>
</tr>
<tr>
<td>Maximum peak discharge current [C]</td>
<td>15C</td>
</tr>
<tr>
<td>Maximum charge current [C]</td>
<td>1C</td>
</tr>
<tr>
<td>Maximum temperature [°C]</td>
<td>60</td>
</tr>
<tr>
<td>Internal resistance [mΩ]</td>
<td>&lt;1.2</td>
</tr>
<tr>
<td>Cycle life</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Weight [g]</td>
<td>308.0</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>85.0</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>154.5</td>
</tr>
<tr>
<td>Thickness [mm]</td>
<td>10.2</td>
</tr>
<tr>
<td>Tab width [mm]</td>
<td>25.0</td>
</tr>
<tr>
<td>Tab length [mm]</td>
<td>10.0</td>
</tr>
</tbody>
</table>

Table 3.6: 16.8 Ah LiPo pouch cell specifications.

The battery is made up of 24 cells with 12 in series and 2 in parallel (12S2P). The assembly design of the battery was done by Jonathan Graesser and is shown in figure 3.5.

The box features sub-boxes that contain the two cells in parallel. Thus, there are twelve boxes that represent the twelve cells in series. The sub-boxes will be printed in ULTEM which is resistant to fire. The handles to lift the battery are made of carbon fiber composite.

The serial connection includes the parallel connection. A close up of the connection is shown in figure 3.6.
Figure 3.6: Close-up on serial connection of cells.

The serial connection is composed by four components:

1. Cell tab (red part in figure 3.6);

2. Copper bar with a cross section of $75 \text{ mm}^2$ (yellow part in figure 3.6);

3. Two steel frames (black parts in figure 3.6);

4. Heatsink (gray part in figure 3.6).

The steel frames are located in between two different cells that are in parallel. Their respective tabs (of the same polarity) are then bent inside the steel frame where the copper and heatsink will sit on top (clamped connection). For easier explanation let us assume a nomenclature as shown in figure 3.7.

Figure 3.7: Serial connection explained.
Cells A and B are in parallel. Their positive tabs are joined in steel frame '1'. Their negative tabs are joined in '2' where a copper bar connects them to the cells C and D that follow the same process. Since A and B are in series with C and D, their tabs polarity is not matching (cell A and B tab polarity is not the cell C and D tab polarity).

The idea of having the heatsinks resting on top of the copper and tabs is to achieve cooling of the cells through their tabs, a process known as tab cooling [7]. Since the tabs are electrically connected to the electrodes, cooling them has a direct impact on internally cooling the battery.

Table 3.7 resumes the final battery specifications.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal voltage [V]</td>
<td>44.4</td>
</tr>
<tr>
<td>Maximum voltage [V]</td>
<td>50.4</td>
</tr>
<tr>
<td>Minimum voltage [V]</td>
<td>36</td>
</tr>
<tr>
<td>Maximum continuous discharge current [C]</td>
<td>10C</td>
</tr>
<tr>
<td>Maximum peak discharge current [C]</td>
<td>15C</td>
</tr>
<tr>
<td>Internal resistance from cells only [mOmega]</td>
<td>&lt;7.2</td>
</tr>
<tr>
<td>Cycle life</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Weight from cells only [kg]</td>
<td>7.39</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>187</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>186</td>
</tr>
<tr>
<td>Height [mm]</td>
<td>169</td>
</tr>
<tr>
<td>Footprint area [mm^2]</td>
<td>0.035</td>
</tr>
<tr>
<td>Volume [L]</td>
<td>5.88</td>
</tr>
</tbody>
</table>

Table 3.7: SR01’s new battery specifications.

This battery will rest inside a box which contains other important electronics and protective components such as the BMS, fuse and safety relay. The box can be seen in figure 3.8.

![Figure 3.8: SR01's new battery box.](image)

Note that the cooling is achieved through fans that blow cool outside air from an air duct (blue part on the left) on top of the heatsinks. This air is then pumped outside the box by the means of outlet fans.
3.4 Experimental data

3.4.1 Cell and battery assembly tests

The cell and battery assembly need to be rigid and of high fidelity since the battery is the most dangerous component of the vessel: a short circuit could burn our prototype - it has happened to other teams during the competition.

The first test consists of checking the rigidity of the serial connection, shown in figure 3.9.

Note that the screws featured in figure 3.9 are only provisionary for testing. The M5 screws that will go on the final battery assembly will have the right dimension.

After checking that all the components were properly fixed, the serial connection resistance from tab to tab was measured, as seen in figure 3.10.

Note that the measurement made here did not take into account the resistance of the multimeter cables. Later a 4-wire resistance measurement was done which indicated a resistance of $2 \, \text{m} \Omega$ for the serial connection.

There are thirteen serial connections thus the battery equivalent resistance stays
\[ R_{eq} = 12 \cdot R_{internal} + 13 \cdot R_{serial} = 33.2 \, \text{m} \Omega. \]  

(3.3)

For the endurance race (1.5 kW, 33.8 A) this means a voltage drop of 1.12 V and a power loss of 38 W or 2.5% of the power drawn.

The sprint race (9 kW, 202.7 A) has a bigger voltage drop - 6.73 V. This reflects a power loss of 1364 W or 15.2% of the power drawn.

### 3.4.2 Cell discharge tests

A single cell was discharge while monitoring its voltage, current and temperature as seen in figure 3.11.

![Cell under discharge](image1)

**Figure 3.11: Cell under discharge.**

A testbench, made by two members of the TSB team, controls the current discharge and opens the circuit in case of under voltage or if the cell is outside its safe operating zone. The testbench is presented in figure 3.12.

![Cell discharge testbench](image2)

**Figure 3.12: Cell discharge testbench.**
The cell was discharged with an average current of $I = 10\, \text{A}$ or $0.6\, \text{C}$. The actual discharge can be seen in figure 3.13.

![Cell experimental current](image)

*Figure 3.13: Cell experimental current.*

The voltage obtained is presented in figure 3.14.

![Cell experimental voltage](image)

*Figure 3.14: Cell experimental voltage.*

The initial temperature of the cell was $24.0\, ^\circ\text{C}$. At the end of the discharge, the cell temperature reached $32.1\, ^\circ\text{C}$ without any cooling system. Summing the current and multiplying by the time, one can
obtain the experimental capacity

$$C_{\text{experimental}} = \sum I \cdot t = 16.4 \text{ Ah.}$$

The experimental capacity is within 3% of the datasheet value. Later, multiple discharge test will be held to have an experimental value on the full battery assembly.
Chapter 4

Mechanical Description of the Vessel

4.1 Mechanical equation

The main objective of this section is to expand on Newton’s second law,

\[ \sum F = ma, \]  \hspace{1cm} (4.1)

in order to derive a function that relates the electrical input power with the vessel’s linear speed. There are multiple forces exerted on the boat; the motor propulsive force and, counteracting that force, the drag forces. Expanding on the drag forces one finds two contributions: the drag created by the air on the frontal area of the vessel (equation (4.2)) and the drag created by the water displacement on the boat’s wet area (equation (4.3)) [8].

\[ F_{\text{air}} = \frac{1}{2} \rho_{\text{air}} A_{\text{air}} c_{d_{\text{air}}} v^2 \]  \hspace{1cm} (4.2)

\[ F_{\text{water}} = \frac{1}{2} \rho_{\text{water}} A_{\text{water}} c_{d} v^2 \]  \hspace{1cm} (4.3)

For aquatic vessels, in order to develop a simpler model, it is plausible to ignore the air drag - the resulting force is four orders of magnitude smaller than the water drag.

Returning to equation (4.1) we find that

\[ F_{\text{motor}} = ma + \frac{1}{2} \rho_{\text{water}} A_{\text{water}} c_{d} v^2. \]  \hspace{1cm} (4.4)

Using the relation between force and power,

\[ P = Fv, \]  \hspace{1cm} (4.5)

we find the function between power and speed of the vessel \( v \)

\[ P_{\text{out}} = mav + \frac{1}{2} \rho_{\text{water}} A_{w} c_{d} v^3. \]  \hspace{1cm} (4.6)
Note that this is the output power of the propeller - in order to find the input power a study on the motor and propeller efficiencies is necessary.

It is possible to simplify the power-speed equation for steady state operation. There is no acceleration therefore it is easy to express the speed of the boat as

\[ v = \sqrt{\frac{2 P_{\text{out}}}{\rho_{\text{water}} A_w c_d}}. \]  

(4.7)

4.2 Drag of the vessel

As seen in equation (4.3), the drag force of a body is defined by its speed and surrounding fluid, but also by the area of contact and various complex dependencies grouped into a constant, \( c_d \).

This constant \( c_d \) is determined experimentally or through simulations. In this thesis, all \( c_d \) values were obtained by the means of computational fluid dynamics (CFD) by members of the TSB team in the hydrodynamics area.

![Figure 4.1: Example of CFD analysis done on SR01's hull.](image)

4.2.1 Drag without hydrofoils

The vessel characteristics are detailed in table 4.1.

| \( A_{\text{water}} [\text{m}^2] \) | 3.26 |
| \( m [\text{kg}] \) | 180 |
| \( c_d \) | 0.0027 |

Table 4.1: SR01’s mechanical details.

Note that the wet area of the boat is considered constant. In reality the area changes with the boat’s speed. The area shown in table 4.1 is the area obtained when the boat is planing on the water at cruise speed. Similarly, the \( c_d \) value is not constant as it is directly related with the area of reference. The weight shown is the total weight of the vessel with the skipper on board (70 kg). Table 4.2 shows the drag obtained by simulation versus the theoretical drag with fixed area and \( c_d \) obtained by the equation (4.3).
<table>
<thead>
<tr>
<th>$v$ [m/s]</th>
<th>Drag theoretical [N]</th>
<th>Drag simulated [N]</th>
<th>$\epsilon$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1</td>
<td>2</td>
<td>43</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>8</td>
<td>43</td>
</tr>
<tr>
<td>1.5</td>
<td>10</td>
<td>18</td>
<td>43</td>
</tr>
<tr>
<td>2</td>
<td>18</td>
<td>32</td>
<td>43</td>
</tr>
<tr>
<td>2.5</td>
<td>28</td>
<td>51</td>
<td>44</td>
</tr>
<tr>
<td>3</td>
<td>41</td>
<td>80</td>
<td>49</td>
</tr>
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<td>3.5</td>
<td>56</td>
<td>100</td>
<td>44</td>
</tr>
<tr>
<td>4</td>
<td>73</td>
<td>143</td>
<td>49</td>
</tr>
<tr>
<td>4.5</td>
<td>92</td>
<td>173</td>
<td>47</td>
</tr>
<tr>
<td>5</td>
<td>113</td>
<td>200</td>
<td>43</td>
</tr>
<tr>
<td>5.5</td>
<td>137</td>
<td>230</td>
<td>40</td>
</tr>
<tr>
<td>6</td>
<td>163</td>
<td>265</td>
<td>38</td>
</tr>
<tr>
<td>6.5</td>
<td>192</td>
<td>280</td>
<td>32</td>
</tr>
<tr>
<td>7</td>
<td>222</td>
<td>310</td>
<td>28</td>
</tr>
<tr>
<td>7.5</td>
<td>255</td>
<td>334</td>
<td>24</td>
</tr>
<tr>
<td>8</td>
<td>290</td>
<td>361</td>
<td>20</td>
</tr>
<tr>
<td>8.5</td>
<td>328</td>
<td>389</td>
<td>16</td>
</tr>
<tr>
<td>9</td>
<td>368</td>
<td>416</td>
<td>12</td>
</tr>
<tr>
<td>9.5</td>
<td>409</td>
<td>445</td>
<td>8</td>
</tr>
<tr>
<td>10</td>
<td>453</td>
<td>475</td>
<td>5</td>
</tr>
<tr>
<td>10.5</td>
<td>500</td>
<td>500</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>549</td>
<td>549</td>
<td>0</td>
</tr>
<tr>
<td>11.5</td>
<td>600</td>
<td>600</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>653</td>
<td>653</td>
<td>0</td>
</tr>
<tr>
<td>12.5</td>
<td>709</td>
<td>709</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>766</td>
<td>766</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4.2: Theoretical and simulated drag of the vessel.

It is clear that considering the area and $c_d$ constant equal to the values obtained for cruise speeds is a lacking model. Therefore, CFD results will be used for the final drag calculations. The theoretical model is then replaced by a look-up table. For speeds between existing values of the table, linear interpolation will be used to deduce results.

### 4.2.2 Drag with hydrofoils

Hydrofoils are wings located under the boat and inside the water. They are used to create lift and remove the hull out of the water, reducing the drag drastically.

SR01’s foil system is composed by three foils in a ‘T’ arrangement, as seen in figure 4.2.
The stern foil is the one that has the propeller in its strut. There are two bow foils - they are identical and provide stabilization to the system.

The foil lift must be variable in order to control the height of the boat in relation to the water. Since lift varies with the angle of attack, the foil chosen includes a control system with stepper motors that is able to vary the foil's angle. The stepper motors are actuated by a PID controller that receives information on the current boat state such as: distance to the water, yaw, pitch and speed in relation to the water (Pitot tube). The PID controller is an ongoing project by two other students in TSB team and is not covered in this thesis.

The foils are designed as such that the take-off speed is $4.5 \text{ m/s}$. The entire system weighs 15 kg. The foil's drag is a complex computation and the angle of attack changes for a given speed. Thus, all the results shown were obtained from CFD.

The total drag of the vessel with foils is calculated considering two bow foils and a stern foil. The drag of the hull is only used up until the take-off speed. The results are shown in the figure 4.3.
It is clear from figure 4.3 that the foil system is beneficent for speeds higher than the take-off speed. However, before the take-off speed there is added drag: both the foils (and their columns) and the hull are submerged. We can plot the power output (mechanical) curve as a function of the speed using equation (4.7).

Figure 4.3: SR01’s drag forces, with foils and without.

Figure 4.4: SR01’s output power in function of the vessel’s speed, with foils and without.
Chapter 5

Electric Propulsion System

5.1 Motor dimensioning

The main event of the competition consist of a race that is 90 minutes long. The 2017’s edition had place between the 13th and 15th of July, with the endurance race scheduled in the morning, between nine o’ clock and eleven o’ clock.

As shown in section 2.2, the average power output of the photovoltaic arrays is $736.6 \text{ W}$. In the case of the battery, there is $1492 \text{ Wh}$ of energy stored that can be spent in 90 minutes. Adding these two contributions gives us the total energy that the boat has available during the race,

$$E_{\text{total}} = 1.5 \cdot P_{\text{photovoltaic}} + E_{\text{battery}} = 2605 \text{ Wh}. \quad (5.1)$$

The average power of the solar array is multiplied by 1.5 in order to account for the hour and a half of race. It is also possible to write down the average power consumed,

$$P_{\text{avg}} = \frac{E_{\text{total}}}{1.5} = 1737 \text{ W}. \quad (5.2)$$

The main electrical load of the boat is the motor but there are other loads to consider. Table 5.1 lists other significant electric loads of the vessel and their respective power consumption.

<table>
<thead>
<tr>
<th></th>
<th>$P_{\text{avg}} \text{ [W]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water pump</td>
<td>12</td>
</tr>
<tr>
<td>Cooling system fans</td>
<td>20</td>
</tr>
<tr>
<td>Safety relays</td>
<td>8</td>
</tr>
<tr>
<td>Foil control system</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 5.1: Some SR01’s electric loads.

Note that multiple components listed have multiple subsystems. For other systems, like the water pump and the foil control system, an average consumption was deduced since those systems aren’t always turned on (ie: the water pump is turned on by the driver whenever he feels like there is too much water inside the hull).
In order to account for the various loads and give some head space for the battery energy, it is fair to consider only 1500 W of average input power (see equation (5.2)) for the motor or 2250 Wh of energy (see equation (5.1)) for the whole race. From this decision the logical choice is to use an electric motor with a nominal power of 1.5 kW which will grant us high efficiency throughout the endurance race. Nevertheless, there are other types of races to consider in the competition - namely the sprint race. After the 2017 edition one of the team’s decision was to have a better sprint performance.

We are faced with a trade-off: having a 1.5 kW motor will ensure the best possible endurance race but a lacking sprint race; having a high powered motor (5 – 10 kW) will bring a great sprint but a not so good endurance race since the motor will be very inefficient at lower powers. A solution to this problem will be proposed in Section 5.2.

5.2 Motor selection

The solution that is suggested in this thesis and implemented for the 2018 competitions is to have two independently controllable motors mechanically coupled to each other and divide the load between them. The objective is to have both motors on full throttle for the sprint and for the endurance there would only be only one motor powering the propeller ensuring high efficiencies.

![Figure 5.1: Example of two motors mechanically coupled to a load.](image)

As seen in figure 5.1, each motor has its pulley and both are connected, by the means of a belt, to the pulley providing the power to load. The motors are always spinning synchronously, therefore it is possible to control their power by their torque since

\[
P_{\text{motor}} = T_{\text{motor}} \cdot \omega, \tag{5.3}
\]

with \( \omega \) being the speed of rotation of both motors and

\[
T_{\text{propeller}} = k \left( T_{\text{motor1}} + T_{\text{motor2}} \right) \tag{5.4}
\]

with \( k \) being the gear ratio, whenever the vessel is in steady state.

For a given propeller torque, the dual motor system may divide the load between the two. This opens
up the possibility of dividing the load in a way that is more optimized since the efficiency depends on the torque and speed.

Both motors are 3 kW BLDC motor from CPMotion (see Appendix B). This motor choice was influenced by several characteristics that were deemed positive:

- Lightweight - each motor weights only 3.7 kg;
- Nominal voltage - the motor voltage is 48 V which fits our 44.4 V battery;
- Power - the nominal power is 3 kW but the motor is capable of peak powers as high as 5 kW;
- Efficiency - the motor has an efficiency of over 89% for 1.5 kW (see figure 5.2), which is our average power input during the endurance race;
- Motor control - the company CPMotion offers a torque controller option which will be used to divide the power between the two motors since their speed is equal.

The efficiency map of the motor is given in the datasheet and can be seen in figure 5.2.

![Figure 5.2: CPMotion 3kW BLDC motor efficiency.](image)
Note that only positive values of torque, the upper part of the graphic, is of interest since the machine will always work as motor - there is no regenerative braking.

5.3 Motor load profile

The objective of this section is to obtain the load parameters of the motors such as the moment of inertia and the load torque characteristic (i.e.: constant torque, quadratic torque, constant power, etc).

As stated in section 5.2, the motors are coupled to a main pulley by the means of a belt. The same idea is used in SR01: both motors have a pulley that is connected to the load pulley. That pulley is then connected to an L-drive that powers the propeller.

![Figure 5.3: SR01’s L-drive.](image1)

![Figure 5.4: SR01’s propulsion column.](image2)

The gear ratio between the motors and the main pulley is three to one ($k = 3$) - the motors spin three times faster than the main pulley. The L-drive has a one to one ratio meaning the propeller spins three times slower than the motors. Table 5.2 resumes moment of inertia and relative spinning speed of the drive system.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Moment of Inertia [gm^2]</th>
<th>Relative speed to propeller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propeller</td>
<td>0.296</td>
<td>1</td>
</tr>
<tr>
<td>Propeller shaft</td>
<td>0.049</td>
<td>1</td>
</tr>
<tr>
<td>L-drive gears (x2)</td>
<td>0.034</td>
<td>1</td>
</tr>
<tr>
<td>Column shaft</td>
<td>0.019</td>
<td>1</td>
</tr>
<tr>
<td>Main pulley</td>
<td>7.114</td>
<td>1</td>
</tr>
<tr>
<td>Motor pulleys (x2)</td>
<td>0.126</td>
<td>3</td>
</tr>
<tr>
<td>Motor (x2)</td>
<td>2.600</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 5.2: SR01’s drive subsystems inertia.

In order to reduce the system to a single moment of inertia at each motor axis, we need to take into account the varying speeds of the subsystems.

Therefore, the total inertia realized at each motor axis is given as
\[ L_{total} = L_{motor} + L_{pulleys} + L_{reflected} \]  \hspace{1cm} (5.5)

with the reflected load at the motor being

\[ L_{reflected} = \frac{L_{load}}{k^2}. \]  \hspace{1cm} (5.6)

The load moment of inertia is compromised by all the subsystems that spin at the same speed as the propeller, thus three times slower than the motors (see table 5.2). The moment of inertia perceived by the motor is

\[ L_{total} = 0.0035 \text{kgm}^2. \]  \hspace{1cm} (5.7)

The load of SR01’s drive is a two blade propeller. Propellers are known for having a quadratic torque profile in relation to the speed of the axis. Thus the load torque should be given as

\[ T_{load} = c \cdot N^2, \]  \hspace{1cm} (5.8)

with \( c \) being a constant. But since the propeller is also moving in relation to the fluid there is a need to have an additional input to compute the propeller torque - the vessel speed. As the vessel speed increases, the propeller does not have to accelerate the fluid as much thus less energy is required from the propeller. This is reflected in the torque that the propeller is demanding. The largest torque is achieved when the vessel is stationary - this is known as the bollard pull and can be used to determine the propeller’s specifications experimentally.

Looking at propeller design theory one is able to describe the propeller torque has

\[ T = f(V_e, N, D, \rho, \nu) \]  \hspace{1cm} (5.9)

with \( V_e \) being the speed of the vessel relative to the fluid, \( N \) the rotation of the propeller, \( D \) the propeller diameter and \( \rho \) and \( \nu \) are the fluid properties: density and kinematic viscosity.

A team member of TSB designed a propeller using OpenProp [9], a open source script for MATLAB. The propeller was designed for the endurance race, achieving the highest efficiency for an input power (mechanical) of 1400 W since the average power available (electrical) is around 1600 W (see equation (5.2)).

Unfortunately, the torque and thrust of the propeller was not explicitly given. Instead information on the advance coefficient, \( J \), or how much the vessel advances during one rotation of the propeller, is given in relation to the torque and thrust.

Figure 5.5 and 5.6 show, respectively, the torque and thrust as a function of the vessel speed and advance coefficient of the propeller.
A script was developed which takes the rotational speed of the propeller and the velocity of the boat and returns the load torque and propeller thrust (see figure A.1 for the flowchart) thus one has

\[
[Torque, Thrust] = f(N, V_e),
\]

which concludes the load characteristics. Note that this model of the propeller is simplified and does not account physical events such as cavitation or the distance between the surface of the water and the propeller being variable due to the foils.
5.4 Dual motor control

There is a need to develop a function that, at any load torque and rotational speed, returns the torque at each motor axis such that the overall losses are minimized. The power loss is given by

\[ P_{loss} = (1 - \eta)T \cdot \omega. \]  

(5.11)

In order to compute the motor efficiency \( \eta \), we need a torque-rotation pair and the efficiency for that point. CPMotion offered the motor efficiency map in matrix form. From that matrix, one can get the efficiency from any rotation-torque pair with a resolution of 0.1 N m and 50 RPM. The map can be plotted as a 3D surface as shown in figure 5.7.

The motor throttle is an input by the skipper - from the lever’s position corresponds a desired torque. This desired torque is divided by the algorithm between the two motors such that the overall power loss is minimized.

The optimal torque for motor 1 and motor 2 for a given load torque and rotation is obtained by brute-forcing all the possible torque pairs and computing the overall loss of the system. Figures 5.8 and 5.9 now show the losses for a given speed of 2000 RPM for two different torques.
The dual motor is shown to be more efficient than the single motor system for high torques (see figure 5.9). For the case of 10 N m at 2000 RPM one can divide the load in half between the two motors, having only 276 W of power losses compared to a 456 W power loss with a single motor driving the whole load - a 40% power loss reduction. In other cases, where the torque is lower (see figure 5.8), using only one of the motors to drive the load is more efficient than dividing it.

Now that we have a way to find the most efficient torque pair for a given rotation and desired torque, one can compute those pairs throughout all the possible rotations. The flowchart of this script is presented in figure A.2. Figures 5.10 and 5.11 show the torque pairs for a desired torque of 10 N m and
5 N m, respectively.

Figure 5.10: Torque pairs for $T = 10$ N m.

Figure 5.11: Torque pairs for $T = 5$ N m.

One can now compute the power loss difference for the single motor and dual motor system in the two previous cases, shown in figures 5.12 and 5.13.
For the 10 N m case, it is clear that dividing the load between the two motors is advantageous as both of the motors work in their region of highest efficiency. This result is clearly seen in figure 5.12 where the power losses of the dual motor system, when compared to a single motor system, is halved from 1000 RPM onwards. In the case of a lower torque, $T = 5 \text{ N m}$, the dual motor system uses only one motor around the 1800 RPM mark onwards. Thus, the dual motor system becomes identical to the single
motor system with the power losses being the same as shown in figure 5.13.

From the study made, it is possible to observe that there are two prominent cases:

1. The desired torque is high and the most efficient torque pair is near 50/50 - half load on each motor;

2. The desired torque is low and the most efficient torque pair is full load on a motor, turning off the other.

Taking that information one can study the case where the dual motor system only has two states: **full load** on motor 1 shutting off motor 2 or **half load on both** of the motors. In this special case there are only two options to compare system losses. Figures 5.14 and 5.15 show the torque pairs for the case of half load-full load for 10 N m and 5 N m, respectively.

![Figure 5.14: Torque pairs for $T = 10$ N m with half load-full load case.](image)
Figure 5.15: Torque pairs for $T = 5 \text{ N m}$ with half load-full load case.

As before the number of merit of the system is the total power loss which can be plotted - see figures 5.16 and 5.17.

Figure 5.16: Losses for $T = 10 \text{ N m}$. 

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In both cases, the power loss of the dual motor system with half load/full load is almost identical to the dual motor system with the best torque pair given by the script developed previously. Thus, the power loss of the dual motor (represented by a green line in figures 5.16 and 5.17) is concealed by the power loss of the dual motor, half load/full load case. Even considering additional mechanical losses due to having a third pulley the dual motor system beats the single motor system, especially for high torques. Also, being able to request high torques is advantageous for our boat: quickly lifting unto the foils to reduce the overall drag is a desired goal.

The dual motor drive with half load/full load is the system that will be implemented due to its lesser losses (when compared to a single high power motor) and feasibility. In the next section we will compute motor losses for various drive cases that will occur during the boat’s drive cycle at the competition, and also determine the torque that the skipper should use in order to accelerate the vessel and lift it onto the foils.

5.5 Experimental testbench

The dual motor system was built and installed in the Electric Machines Laboratory as seen in figure 5.18.
The two BLDC motors are held in place with the help of an aluminium support structure. Note that the pulleys and belt seen in figure 5.18 are the same that will be featured in the boat. The motors are fed by a DC power source with a nominal voltage of 48 V with the capacity of delivering a current of 62 A (3 kW).

The motor control is achieved by CAN communication. The TSB member João Pinto developed a PCB, seen in figure 5.20, that handles the communication with the motors. The PCB features a microcontroller that runs the load control script developed previously (see Appendix A.2 for the script flowchart) and logs the sensors data of the motor.

The load is a 3 kW nominal power synchronous generator with two pairs of poles. Thus its nominal rotational speed is

\[
N_n = \frac{60 \cdot 50}{N_{PP}} = 1500 \text{ RPM.}
\]  

(5.12)

Given that the transmission ratio is three, the nominal speed for our motors will be 4500 RPM. This
means that for speeds lower than 4500 RPM it will be difficult to achieve the load’s nominal power.

The generator has its rotor fed by a DC power source and the three stator phases are connected, in star, to a three-phase resistive load (see figure 5.21).

The global system is represented in figure 5.22.

In order to characterize the generator, simple tests were performed where the stator output voltage was measured while changing the generator speed, as seen in table 5.3.
<table>
<thead>
<tr>
<th>Excitation current [A]</th>
<th>N [RPM]</th>
<th>Stator phase-neutral voltage [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>500</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>667</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>833</td>
<td>97</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>117</td>
</tr>
<tr>
<td></td>
<td>1167</td>
<td>136</td>
</tr>
</tbody>
</table>

Table 5.3: Synchronous generator stator voltage in function of its rotational speed.

Visually the motor testbench is not vibrating a lot which is a good sign for the mechanical coupling. An FFT of the generator stator voltage was performed in the oscilloscope for the speeds shown in table 5.3 in order to analyse the harmonics in the output voltage. Since the voltage frequency comes from the rotational frequency of the rotor one can, by reading the stator voltage harmonics, verify if the rotor is vibrating. Figure 5.23 displays the FFT for a rotational speed of 1000 RPM (3000 RPM for the motors).

![Figure 5.23: Harmonics of the stator voltage for \( N = 1000 \text{ RPM} \).](image)

Since the generator has two pole pairs the electrical frequency is two times the mechanical frequency of the rotor, 2000 RPM or 33.3 Hz. It is possible to observe, at 33.3 Hz an amplitude of 64 dB - all other frequencies are at least 20 dB below. The testbench is therefore deemed good enough for tests. The actual system for the boat will be manufactured more properly and the belt alignment improved on.

### 5.5.1 Dual motor load division

To validate the torque load division, a script was developed that cycles the motors torques every 15 seconds between the following three cases:

1. M1 drives the full torque;
2. M1 and M2 drive half torque each;
3. M2 drives the full torque.

Figure 5.24 displays the torque requests to the dual motor system.
The requested torque is actually a requested current [10] obtained by

\[ T = K_t \cdot I_q \]  \hspace{1cm} (5.13)

where \( K_t \) is the torque constant of the motor. Figure 5.25 shows the requested current for motor 2, as well as the actual current.
It is possible to observe in figure 5.25 that the motor response time is fast enough with the actual current following the behaviour of the requested current. It is also possible to represent the global system torque. This is done by summing both of the motor currents and multiplying them by the torque constant (see equation (5.13)) - the result is shown in figure 5.26.
Figure 5.26: Dual motor system torque output with varying torque pairs (figure 5.24).

There is no visible real torque variation detected from the commutation of a single motor driving the full load to both motors driving half load each. The speed of the motors is presented in figure 5.27.

Figure 5.27: Motors speed.
As it is possible to observe from figure 5.27 the rotational speed of the global system is not constant. There is a 10% difference between the minimum and maximum speed.

During the tests it was possible to see that whenever motor 2 was driving the full load, the system speed would reduce. In fact, motor 2 is the motor that is furthest away from the load since there is an additional pulley between him and the generator as seen in figure 5.28.

![Figure 5.28: Motors testbench schematic.](image)

It was possible to observe that after the first pulley, the belt would become looser. This is what is believed to be the cause of motor 2 not being capable of transferring its torque efficiently to the load. To prove this assumption the direction of rotation was reversed - this time motor 2 had a direct connection to the load. The result was the same as before but inverted - whenever motor 1 was driving the full load, the system speed would reduce.

The final dual motor system will have an additional pulley that is spring loaded to maintain tension on the belt between the motors.

### 5.5.2 Thermal tests

As the dual motor system has, during cruise speed, only one motor driving the propeller it is possible to change the main motor whenever it overheats. To prove this concept, the testbench load was unchanged during the tests and the desired torque was set to around $3.1\, \text{N} \cdot \text{m}$. The motors’ temperature were recorded, thanks to the motor communication PCB, without any external cooling system. First only one motor is driven until a temperature of $60\, ^\circ\text{C}$ as seen in figures 5.29 and 5.30.
It took 500 s for a single motor, pulling around 2 kW, to reach a temperature of 60 °C. Note that motor 2 is also heating up since it is also spinning (friction losses). Now let us imagine a case where, whenever the main driving motor reaches a certain temperature, the main motor is switched. For this test, the threshold temperature set was 55 °C and the torque requested for each motor as well as their temperatures are shown in figures 5.31 and 5.32, respectively.
Here, even after 600 s (100 s longer than the single motor test) both of the motor are below 60 °C. The dual motor system divides the load, in time, between the two motors ensuring a lower global temperature and thus a greater efficiency of the powertrain.
Chapter 6

Driving Cycles

6.1 Electromechanical equation

6.1.1 Constant speed

The objective of this section is to develop a function that returns the electrical power needed for a given output speed. The function has to account for the varying efficiency of two systems: the two electric motors featured in the dual drive and the propeller.

When considering the acceleration of the vessel zero it is possible to relate the drag force of the hull with the thrust of the propeller as

\[ \text{Thrust} = \text{Drag}. \]

(6.1)

The drag value is then interpolated in the thrust matrix of the propeller in the desired speed column (see figure 5.6) which returns the rotational speed of the propeller in RPM with the advance coefficient \( J \) which is given as

\[ J = \frac{v \cdot 60}{D \cdot N}, \]

(6.2)

where \( D \) is the propeller blade diameter. The advance coefficient is use to access, with the speed, the torque matrix of the propeller and compute the load torque \( T_{prop} \). This torque is used to calculate the motor output torque,

\[ T_{motor} = \eta_{gears} \cdot T_{prop}. \]

(6.3)

Finally the electromagnetic torque of the motor is computed by

\[ T_{em} = \eta_{dualmotor}(N, T_{motor}) \cdot T_{motor}. \]

(6.4)

It is therefore possible to achieve the input electrical power of the motor for a speed as
As an example let us assume a speed of $6 \text{ m/s}$, the drag for SR01 with foils is $\text{Drag} = 113.1 \text{ N}$ and without foils is $\text{Drag} = 265 \text{ N}$. For the sake of this example let us assume SR01 is flying on top of the foils.

Accessing the thrust matrix in the $6 \text{ m/s}$ column it is possible to conclude the advance coefficient is located between 1.4 and 1.5 - a simple linear interpolation yields $J_{\text{em/s}} = 1.41$ giving us a rotational speed of 664.89 RPM for the propeller, therefore the motor is spinning at three times the speed, 1994.7 RPM.

The torque matrix is now interpolated using the advance coefficient previously found, $J_{\text{em/s}} = 1.41$, in order to retrieve a torque - in this case $T_{\text{prop}} = 3.44 \text{ N m}$. Considering a gear efficiency of 95% we have $T_{\text{motor}} = 3.62 \text{ N m}$.

The electromagnetic torque is computed by trial and error with torques superior the the motor torque until $T_{\text{em}} = \frac{T_{\text{motor}}}{\eta_{\text{motor}}(N,T_{\text{em}})}$. Note that the speed of the motor is given before with the calculation of the advance coefficient and the efficiency of the motor computed here has into account the splitting of the load whenever this solution proves to be more efficient. Interpolating the efficiency map values of the motor yields $T_{\text{em}} = 3.93 \text{ N m}$. In order for SR01 to travel at $6 \text{ m/s}$ the propulsion system must consume

$$P_{\text{in}}(6) = 906 \text{ W}. \quad (6.6)$$

Table 6.1 resumes the power input (electrical) of the powertrain for multiple speeds, with a single motor and with the dual motor system, as well as the powertrain efficiency considering foils.
Table 6.1: Power input (electrical) and powertrain efficiency for multiple speeds (with foils).

<table>
<thead>
<tr>
<th>Single motor</th>
<th>Dual motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed [m/s]</td>
<td>Power input [W]</td>
</tr>
<tr>
<td>4.5</td>
<td>386</td>
</tr>
<tr>
<td>5</td>
<td>526</td>
</tr>
<tr>
<td>6</td>
<td>906</td>
</tr>
<tr>
<td>7</td>
<td>1419</td>
</tr>
<tr>
<td>8</td>
<td>2135</td>
</tr>
<tr>
<td>9</td>
<td>3088</td>
</tr>
<tr>
<td>10</td>
<td>4601</td>
</tr>
<tr>
<td>11</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>-</td>
</tr>
</tbody>
</table>

Note that the powertrain efficiency is the same for the single motor and dual motor until 7 m/s - this is when the dual motor system engages the second motor due to the high load torque required to travel at such speeds. The dual motor system also allows the vessel to travel at higher speeds since the propulsive power installed is doubled from the single motor system.

Table 6.2 now resumes the power input (electrical) of the powertrain for multiple speeds as well as the powertrain efficiency but this time for SR01 without foils.

<table>
<thead>
<tr>
<th>Single motor</th>
<th>Dual motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>Power input [W]</td>
</tr>
<tr>
<td>4.5</td>
<td>1102</td>
</tr>
<tr>
<td>5</td>
<td>1311</td>
</tr>
<tr>
<td>6</td>
<td>2054</td>
</tr>
<tr>
<td>7</td>
<td>3747</td>
</tr>
<tr>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 6.2: Power input (electrical) and powertrain efficiency for multiple speeds (without foils).

6.1.2 Accelerations

In Subsection 6.1.1 a way of computing the input electric power of the propulsion system in relation to the vessel speed was developed. In this Subsection the objective is to compute, for several torques (the input of the throttle controlled by the driver), the energy spent from an initial speed to a final speed.

The script written for this objective has three inputs:

1. Desired torque, $T_{\text{desired}}$, the only input controlled by the skipper;
2. Motor rotation, $N_{\text{motor}}$, the initial motor speed;
3. Vessel speed, $v$, the initial speed.

Having the motor rotation and speed of the vessel it is possible to access the propeller matrices (see Section 5.3) to retrieve the thrust, $\text{Thrust}$, and torque of the propeller, $T_{\text{prop}}$. 

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The actual motor torque, \( T_{\text{motor}} \), that reaches the propeller is computed with the desired torque taking into account the gears efficiency and the dual motor efficiency:

\[
T_{\text{motor}} = \eta(T_{\text{desired}}, N_{\text{motor}}) \cdot T_{\text{desired}}. \tag{6.7}
\]

In equation (6.7) \( \eta(T_{\text{desired}}, N_{\text{motor}}) \) is obtained from the algorithm developed in Section 5.4 for the dual motor efficiency.

The angular acceleration of the propeller is given as

\[
\alpha = \frac{k \cdot T_{\text{motor}} - T_{\text{prop}}}{L} \tag{6.8}
\]

with \( L \) being the moment of inertia computed in Section 5.3.

SR01’s drag is obtained by interpolating the drag table (see figure 4.3) with the input speed - here it is possible to choose SR01 with or without foils. The acceleration is given as

\[
a = \frac{\text{Thrust} - \text{Drag}}{m}. \tag{6.9}
\]

It is now possible to update the speed and rotation of the motor:

\[
v_{i+1} = v_i + a \cdot t, \tag{6.10}
\]

\[
N_{\text{motor}, i+1} = N_{\text{motor}, i} + \frac{60 \cdot \alpha \cdot t}{2\pi}. \tag{6.11}
\]

Meanwhile the power input and output of the motor and propeller are given as

\[
\text{Power}_{\text{input}} = T_{\text{desired}} \cdot N_{\text{motor}} \frac{2\pi}{60} \tag{6.12}
\]

\[
\text{Power}_{\text{shaft}} = T_{\text{motor}} \cdot N_{\text{motor}} \frac{2\pi}{60} \tag{6.13}
\]

\[
\text{Power}_{\text{output}} = \text{Thrust} \cdot v \tag{6.14}
\]

Finally the energy spent is calculated by sum of the multiple points of power multiplied by the time resolution

\[
E = \sum \text{Power} \cdot t. \tag{6.15}
\]

The flowchart of this script can be seen in figure A.3. As an example let us assume the following case: the boat is almost stopped and the skipper puts the throttle forward such that \( T_{\text{desired}} = 10 \text{ N m} \) and the initial parameters are \( N_{\text{motor}} = 500 \text{ RPM} \) and \( v = 0.5 \text{ m/s} \). This acceleration is maintained until the vessel speed reaches \( 7 \text{ m/s} \). The evolution of the vessel speed can be seen in figure 6.2.
Figure 6.2: SR01’s speed for an acceleration with $T_{desired} = 10 \text{ N m}$.

The motor rotational speed during the acceleration is also shown in figure 6.3.

Figure 6.3: SR01’s motor rotational speed for an acceleration with $T_{desired} = 10 \text{ N m}$.

The propeller torque (load torque) is represented and compared to the shaft torque (see equation (6.7)) in figure 6.4 and the thrust of the propeller is shown in figure 6.5.
Figure 6.4: Shaft and propeller torque for an acceleration with $T_{desired} = 10$ N m.

Note that the motor actual torque, in figure 6.4, is multiplied by the gear ratio to have the motor torque seen by the propeller. The difference between the two is the resulting shaft angular acceleration.

Figure 6.5: Propeller thrust for an acceleration with $T_{desired} = 10$ N m.

In figure 6.5, the thrust of the propeller is represented. It is with that value, compared to the boat drag, that one can compute the vessel acceleration.

Finally the power input and output of the motor and propeller during the acceleration are drawn in figure 6.6.
Figure 6.6: Power conversion of the powertrain for an acceleration with $T_{\text{desired}} = 10$ N m.

This is a very interesting figure: it is possible to view the motor power losses (difference between the power input and power at the shaft) and also the propeller power losses (difference between the power at the shaft and the power output). The global power loss is also given by comparing the input power to the output power. Note that, in figure 6.6, the propeller is very inefficient at low vessel speeds (low advance coefficient) because it has to transfer more power in order to accelerate the fluid that passes through it.

For this acceleration the vessel travelled 22.2 m and took 5.9 s to reach 7 m/s. The total power spent (electrical) was $4.38$ Wh. It is possible, from figure 6.6, to obtain the powertrain efficiency for any given point. It is also interesting to compute the average efficiency of the powertrain during the acceleration which is obtained by

$$\eta_{\text{avg}} = \frac{E_{\text{out}}}{E_{\text{in}}}.$$  \hspace{1cm} (6.16)

Table 6.3 resumes the energy of each part of the powertrain.

<table>
<thead>
<tr>
<th>Energy Type</th>
<th>Value [Wh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{input}}$</td>
<td>4.38</td>
</tr>
<tr>
<td>$E_{\text{shaft}}$</td>
<td>3.88</td>
</tr>
<tr>
<td>$E_{\text{output}}$</td>
<td>2.45</td>
</tr>
</tbody>
</table>

Table 6.3: Energy of each part of the powertrain for the example acceleration.

The average efficiency of each subsystem and the global powertrain is presented in table 6.4
Motor efficiency 0.88  
Propeller efficiency 0.63  
Powertrain efficiency 0.56  

Table 6.4: Average efficiency of the powertrain for the example acceleration.

This script can be used in order to compute the energy spent from any given initial speed to any given reasonable final speed.

6.2 Endurance race

The 2017 edition featured a route with three buoy, as seen in the figure 6.7.

![Figure 6.7: Monaco solar and electric boat challenge 2017 route.](image)

Using the scale found in the bottom left it is possible to find the distances of the course. Between the two farthest buoy there are 439 m and from the team’s footage one lap took on average three minutes and thirty seconds. Both of the turns took around twelve seconds to complete. SR01’s average speed was $3.83 \text{ m/s}$.

From this data it is plausible to assume the boat spends 11.5% of its time in curves. We will use this assumption in order to compute energy needs of the vessel. There are now two distinct cases that needs to be analysed: curving on top of the foils and curving with the hull in the water.

As of this time it is still not possible to say if the boat will curve on top of the foils - it is dependent on how well our PID controller is dimensioned.

The winning team of ‘A class’ in 2017, NHL Solarboattteam, did twenty eight laps. This amounts to an average speed of $5 \text{ m/s}$ considering one and a half hours of race.

Note that the energy available to the propulsion system was computed in equation (5.1) and is equal to 2605 Wh. This energy can be decomposed into three portions,

$$E_{\text{total}} = E_{\text{acc}} + E_{\text{straight}} + E_{\text{curves}}. \quad (6.17)$$
In order to understand better the driving cycle of the endurance race one can simplify it by considering three phases:

1. Acceleration phase;
2. Cruise speed phase;
3. Curve phase.

The endurance race can be divided into these three phases for the 439 m between the buoys as shown in figure 6.8.

![Figure 6.8: Endurance race track model.](image)

Between points 1 and 2 SR01 is exiting the curve and accelerating to its cruise speed. The segment from 2 to 3 represents the distance until the next buoy where the boat is sailing in a straight line at constant speed - this is the cruise phase of the vessel. Finally, between 3 and 4 is the curve - the model then starts over at point 1 (exiting the curve). Note that the deacceleration phase is not considered: this model assumes that the cruise speed is maintained up until the curve (worst case).

For each lap the track model presented in figure 6.8 is completed twice (going to the furthest buoy and back).

It is now possible to compute the energy consumed in each segment with the scripts previously developed in Subsections 6.1.1 and 6.1.2. There are three inputs for the scripts - \( T_{\text{desired}} \), the torque requested by the skipper during the acceleration phase; \( v_{\text{cruise}} \), the vessel cruise speed during the constant speed phase; \( v_{\text{curve}} \), the vessel speed during the curve phase.

The scripts will return the time and energy spent for the track model. It is then possible to compute the number of laps that SR01 will travel as well as the total energy spent.

As a first example let us compute the performance of SR01 with

- \( T_{\text{desired}} = 10 \text{ N m} \);
- \( v_{\text{cruise}} = 7 \text{ m/s} \);
- \( v_{\text{curve}} = 4.5 \text{ m/s} \).

First, using the acceleration script (Subsection 6.1.2) with \( T_{\text{desired}} = 10 \text{ N m} \) from \( v_{\text{curve}} \) to \( v_{\text{cruise}} \) yields the following results resumed in table 6.5.

<table>
<thead>
<tr>
<th>Distance travelled [m]</th>
<th>Time spent [s]</th>
<th>Energy spent [Wh]</th>
<th>Powertrain efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.6</td>
<td>2.3</td>
<td>1.82</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Table 6.5: Acceleration phase with \( T_{\text{desired}} = 10 \text{ N m} \).
It is now possible to compute the energy and time spent during the cruise speed phase - the distance to travel is given by the total distance between buoys (439 m) minus the distance already travelled during the acceleration. Table 6.6 presents the information obtained from the script for $v_{\text{cruise}} = 7 \text{ m/s}$.

<table>
<thead>
<tr>
<th>Distance left [m]</th>
<th>Time spent [s]</th>
<th>Energy spent [Wh]</th>
<th>Powertrain efficiency</th>
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</thead>
<tbody>
<tr>
<td>426.4</td>
<td>60.9</td>
<td>24.01</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Table 6.6: Cruise speed phase with $v_{\text{cruise}} = 7 \text{ m/s}$.

The acceleration and cruise speed phase return a time of 60.9 s. Taking into account the assumption that the vessel spends 11.5% of its time curving yields $t_{\text{curve}} = 8.2 \text{ s}$. The calculations for the curve energy are identical to the ones for the cruise speed phase. Table 6.7 shows the values obtained.

<table>
<thead>
<tr>
<th>Time spent [s]</th>
<th>Energy spent [Wh]</th>
<th>Powertrain efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.2</td>
<td>0.88</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Table 6.7: Curve phase with $v_{\text{curve}} = 4.5 \text{ m/s}$.

Thus the track model is completely modelled in terms of speed and energy spent - the final results can be found in table 6.8.

<table>
<thead>
<tr>
<th>Track time [s]</th>
<th>Total energy [m]</th>
<th>$N_{\text{laps}}$</th>
<th>Total time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>71.4</td>
<td>26.7</td>
<td>51.7</td>
<td>123</td>
</tr>
</tbody>
</table>

Table 6.8: Endurance race performance.

The number of possible laps, $N_{\text{laps}}$ in table 6.8, is determined by dividing the energy available by the energy spent per lap,

$$N_{\text{laps}} = \frac{E_{\text{available}}}{E_{\text{lap}}} = \frac{E_{\text{available}}}{2 \cdot E_{\text{track}}} \quad (6.18)$$

The total time is then obtained by multiplying the number of laps with the respective lap time:

$$t_{\text{total}} = N_{\text{laps}} \cdot t_{\text{lap}} = N_{\text{laps}} \cdot 2 \cdot t_{\text{track}} \quad (6.19)$$

The total time obtained for this particular example was 123 minutes - since the race time is 90 minutes this means that SR01 could actually spend more energy. Spending more energy is achieved by either tweaking the acceleration torque or rising the cruise speed of the vessel. The curve speed is determined to be 4.5 m/s since it is the minimum speed at which the vessel can stay on the foils.

Table 6.9 resumes the performance of SR01 for multiple acceleration torques and cruise speeds with the dual motor system.
Cruise speed [m/s] | Acceleration torque [Nm] | $N_{\text{laps}}$ | Total time [min]  
---|---|---|---  
6 | 10 | 68.2 | 189  
 | 14 | 67.8 | 187  
 | 20 | 67.1 | 185  
 | 25 | 66.6 | 184  
7 | 10 | 51.7 | 123  
 | 14 | 51.4 | 122  
 | 20 | 50.7 | 120  
 | 25 | 50.1 | 119  
8 | 10 | 40.3 | 84  
 | 14 | 40.0 | 83  
 | 20 | 39.5 | 82  
 | 25 | 39.0 | 81  

Table 6.9: SR01’s performance for multiple cruise speeds and acceleration torques with a dual motor drive.

In order to compare the performance of the dual motor system, the same table as 6.9 but with a single motor is shown in 6.10.

Cruise speed [m/s] | Acceleration torque [Nm] | $N_{\text{laps}}$ | Total time [min]  
---|---|---|---  
6 | 10 | 67.9 | 188  
 | 14 | 67.4 | 186  
 | 20 | - | -  
 | 25 | - | -  
7 | 10 | 51.4 | 123  
 | 14 | 51.0 | 121  
 | 20 | - | -  
 | 25 | - | -  
8 | 10 | 40.0 | 84  
 | 14 | 39.6 | 83  
 | 20 | - | -  
 | 25 | - | -  

Table 6.10: SR01’s performance for multiple cruise speeds and acceleration torques with a single motor drive.

It is possible to witness, in tables 6.9 and 6.10, that the dual motor system prevails in all cases since both of the motors are used for the accelerations, although the difference is not significant. The acceleration torques tested start at 10 N m - this is because under 8 N m the vessel is not capable or reaching the necessary thrust to overcome the hull drag and rise unto the foils.

To conclude, the dual motor system is, for all cases, either equal or better than the single motor system. For the calculated available energy SR01’s cruise speed will be somewhere between 7 and 8 m/s, depending on the sun’s irradiance the day of the race. The dual motor system, compared with the single motor system, will be even more efficient as the available energy increases.

6.2.1 Without foils

In case the foil system fails, the following table 6.11 details the expected performance of both single and dual motor drive in the endurance race. The calculations are the same as in Section 6.2.
<table>
<thead>
<tr>
<th>Cruise speed [m/s]</th>
<th>Acceleration torque [Nm]</th>
<th>Dual motor</th>
<th>Single motor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$N_{\text{max}}$</td>
<td>Total time [min]</td>
<td>$N_{\text{max}}$</td>
</tr>
<tr>
<td>5</td>
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<td>22.2</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>22.1</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 6.11: Single and dual motor drive performance of SR01 in the endurance race, without foils.

For the no foil case, the single motor and dual motor drive have identical performances. In these cases, SR01 will be capable of completing around 32 laps in the hour and a half of endurance race.

### 6.3 Sprint race

The sprint race consists of a straight line where the vessel accelerates to its maximum speed. The objective of this Section is to estimate the maximum speed SR01 is capable of reaching with the current dual motor drive.

In order to compute the speed the script developed in Section 6.1.2 will be employed here. First let us test the single motor drive which is capable of delivering a peak torque of 14 N m and peak power of 5 kW. Therefore the script will have the following inputs:

- $T_{\text{desired}} = 14 \text{ N m}$;

- Maximum Power input of 5 kW.

The maximum speed of 10.4 m/s is reached within 16.5 s, as seen in figure 6.9.
The propulsion system is capable of delivering a power output of 3577 W with an efficiency of $\eta = 0.72$ (see figure 6.10).

For the dual motor drive the peak torque is 28 Nm and the peak power 10 kW. In this case the propulsion system is capable of delivering over 7500 W and the maximum speed is over 13 m/s as it is
possible to see in figures 6.11 and 6.12.

Figure 6.11: SR01 power evolution in sprint for the dual motor drive.

Figure 6.12: SR01 speed evolution in sprint for the dual motor drive.

Unfortunately the propeller model exists only for speeds under $13 \text{ m/s}$ as previously the TSB team did not believe the boat could reach such high speeds. The dual motor system, when compared to a
single motor drive, is capable of delivering 100% more propulsion power. It is clear that the dual motor system is advantageous to a single motor in the sprint race.

6.3.1 Without foils

In the case that the foils control fails let us compute the expected speed for both single and dual motor drive. The computation is the same as before with the foils but this time with the drag of the hull.

With a single motor it is possible to achieve 8.9 m/s as seen in figure 6.13.

![Figure 6.13: SR01 speed evolution in sprint for the dual motor drive without foils.](image)

With the proposed dual motor drive, without foils, SR01 is capable of achieving 11.3 m/s.
Without foils the dual motor system, in comparison with a single motor drive, allows for a speed increase of 27%. In the 2017 edition, SR01 reached a speed of 6.8 m/s, without foils. The dual motor system will increase, in comparison with last year, our maximum speed in 66%.
Chapter 7

Conclusions

7.1 Achievements

This work as proven, experimentally, that two motors mechanically coupled with independent torque control is a valid system with enough fidelity to be installed in SR01 for the 2018’s competitions. The final system to be installed in the vessel is shown in figure 7.1.

Note, in figure 7.1, there is an extra pulley in between the two motors that is spring loaded in order to maintain tension on the belt - the spring restoring force is still unknown and will be tested when the system is assembled (early June 2018). Both of the motor shafts are supported by an additional bearing on top of the box (see topmost motor in figure 7.1) since the torque obtained by the dual motor drive creates radial forces superior to the motor maximum rating.

This work also proved, by means of theoretical calculations and simulations, that the dual motor system has no impact on the performance of SR01 for the endurance race when compared to a single
motor drive. The dual motor drive also allows higher torques for accelerating, an important feature to help SR01 lift itself unto the foils as soon as possible.

As for the goal of improving the sprint race, the dual motor system increases the top speed of SR01 in 25% - with the help of the foils the team might break the 45 km/h barrier in 2018.

7.2 Future work

7.2.1 Future work until 2018 competitions

For the driving cycle of the endurance race, both $T_{\text{desired}}$ and $v_{\text{cruise}}$ are chosen by hand. An optimization script will be developed that has those two inputs and wishes to minimize the energy consumption while maximizing the vessel's average speed. The objective is to find the best accelerations and speeds possible that SR01 can use in order to complete as many laps as possible during the 90 minutes of the endurance race.

The motor dual system will be tested on the boat, coupled to its real load: the vessel's propeller. Real consumption data will be compared with the simulation results presented in this thesis. The motor torque and vessel speed will be obtained in order to understand if the propeller model is valid, as well as the dual motor system efficiency.

The battery cells will be discharged at various C-ratings in order to get a experimental capacity and compare that value with the datasheet number. A full battery discharge, inside the battery box, will be held to analyse the thermal dynamic of the cells and verify the tab cooling system. The results will be vital to dimension the cooling system fans and intake tube cross-sectional area.

7.2.2 Future work after 2018 competitions

After the competitions, there will be a lot of experimental data to analyse.

The solar arrays voltage, controlled by the MPPTs, will be studied to understand the maximum power point tracking algorithm and also create a model for the partial shading probability.

The driving cycle of the endurance race will be thoroughly studied to understand the curve speeds and the vessel's take-off unto the foils, both torque requested and the lift obtained - the vessel's accelerations are all logged by an inertial measurement unit.

An interesting work would be to develop a variable pitch propeller with the pitch controller by stepper motors. By varying the pitch of the propeller one changes the propeller torque demand for a certain angular velocity. Coupled with a torque control drive, one could actually change the load in order to maintain both the motor and propeller in their high efficiency zones.
In figure 7.2 the motor is set to a torque of 5 N m. It is possible to see that by reducing the pitch of the propeller, the motor speeds up since the torque of the propeller is reduced. This can be controlled in order to guide the load perceived by the motor to its most efficient zones.
References


[3] Nasa langley research center atmospheric science data center surface meteorological and solar energy (sse) web portal supported by the nasa larc power project [accessed 08-10-2017].


[8] Nasa glenn research center, the drag equation [accessed 24-11-2017].


Appendix A

Scripts

Figure A.1: Flowchart of the script that returns the propeller torque and thrust from the vessel speed and propeller RPM.
Figure A.2: Flowchart of the script that returns the torque pairs for a given torque for all RPM.
Figure A.3: Flowchart of the script that returns the acceleration performance of SR01 for a given desired torque.
Appendix B

Technical Datasheets
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Get your money’s worth with Genasun. A true problem-solver, the unique GVB charge controller with MPPT allows a lower-voltage solar panel to charge higher-voltage batteries. Want to charge a 24V battery with a 48-cell solar panel? No problem. A 48V battery from a 12V panel? We’ve got you covered. With 99% peak efficiency and the ability to charge with as little as 5V of input, they are the industry’s most efficient voltage-boosting controllers.

GVB-8 8A MPPT @ 12-48V

Take advantage of Genasun’s advanced MPPT technology and enjoy more reliable power from smaller panels.

Specifications:

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<th>GVB-8-Pb-12V</th>
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</tbody>
</table>

*Panel ratings have increased since we designed the GVB. Although we don’t believe in changing specifications without a corresponding engineering change, based on both our customers’ experiences over the years as well as the headroom we designed into the GVB, we feel comfortable recommending the GVB for panels with Imp up to 8A.

**Panel Isc. Maximum input power and maximum input voltage requirements must also be respected.

***Maximum current that the controller could draw from an unlimited source.

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The compact power BLDC CPM90 comprises of a brushless, permanent-magnet synchro-motors as well as a fully integrated control unit. It is exhibiting a maximum efficiency -over 90%- for all low voltage applications.

**Features & Benefits**

- Brushless DC motor with integrated CAN bus control electronics
- Torque up to 14 Nm peak
- Supply voltage range between 38V and 56V
- Protection index up to IP54
- Outstanding, compactness
- Torque control/Speed control
- Power/Battery current control
- Energy recuperation
- Field oriented control

**Dimensions**

**Technical data**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating voltage</td>
<td>36 – 56 V</td>
</tr>
<tr>
<td>Max torque</td>
<td>14 Nm</td>
</tr>
<tr>
<td>Max speed</td>
<td>6000 rpm</td>
</tr>
</tbody>
</table>

**Efficiency Map**

**Electrical and Mechanical Interface**

**Integrated signal connector**

Souriau UTS1JC1412P

**Signal connector pinout**

1=CAN high, 2=CAN low, 3=Analog in 2, 4=Analog in 1, 5=Digital IO 1, 6=Killswitch, 7=Digital IO 3, 8=Digital IO 2, 9=Signal GND, 10=Vout, 11=Digital out 4, 12=not used

**Screw terminals for power supply**

2x M6 bolts

**Communication**

CAN

**Over and under voltage protection**

Integrated

**Maximum battery current**

150 A

**Output shaft**

2 flats, spline, feather key (others on demand)

**Operating conditions**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Temp. Range</td>
<td>-40°C / +60°C</td>
</tr>
<tr>
<td>Protection class</td>
<td>Up to IP 54</td>
</tr>
<tr>
<td>ROHS (Lead Free)</td>
<td>Compliant</td>
</tr>
</tbody>
</table>

Special requirements upon customer specifications. Right to change without notifications reserved.
The SunPower™ C60 solar cell with proprietary Maxeon™ cell technology delivers today’s highest efficiency and performance. The anti-reflective coating and the reduced voltage-temperature coefficients provide outstanding energy delivery per peak power watt. Our innovative all-back contact design moves gridlines to the back of the cell, which not only generates more power, but also presents a more attractive cell design compared to conventional cells.

Maximum Light Capture
SunPower’s all-back contact cell design moves gridlines to the back of the cell, leaving the entire front surface exposed to sunlight, enabling up to 10% more sunlight capture than conventional cells.

Superior Temperature Performance
Due to lower temperature coefficients and lower normal cell operating temperatures, our cells generate more energy at higher temperatures compared to standard c-Si solar cells.

No Light-Induced Degradation
SunPower n-type solar cells don’t lose 3% of their initial power once exposed to sunlight as they are not subject to light-induced degradation like conventional p-type c-Si cells.

Broad Spectral Response
SunPower cells capture more light from the blue and infrared parts of the spectrum, enabling higher performance in overcast and low-light conditions.

Broad Range Of Application
SunPower cells provide reliable performance in a broad range of applications for years to come.

Electrical Characteristics of Typical Cell at Standard Test Conditions (STC)

<table>
<thead>
<tr>
<th>Bin</th>
<th>Pmpp (Wp)</th>
<th>BEl (mV)</th>
<th>Vmpp (V)</th>
<th>Impp (A)</th>
<th>Voc (V)</th>
<th>Isc (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>3.34</td>
<td>21.8</td>
<td>0.574</td>
<td>0.682</td>
<td>6.24</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>3.38</td>
<td>22.1</td>
<td>0.577</td>
<td>0.684</td>
<td>6.26</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>3.40</td>
<td>22.3</td>
<td>0.581</td>
<td>0.686</td>
<td>6.27</td>
<td></td>
</tr>
<tr>
<td>J</td>
<td>3.42</td>
<td>22.5</td>
<td>0.582</td>
<td>0.687</td>
<td>6.28</td>
<td></td>
</tr>
</tbody>
</table>

All Electrical Characteristics parameters are nominal

Unlimited Cell Temperature Coefficients
Voltage: -1.8 mV / °C             Power: -0.32% / °C

TYPICAL I-V CURVE

Spectral Response

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此规格书适用于深圳市风云电池有限公司的锂聚合物可充电电池产品

The specification is suitable for the performance of Lithium-Polymer (LIP) rechargeable battery produced by the SHENZHEN MELASTA BATTERY CO., LTD.

2. 型号 MODE

SLPBA885155HT 16800mAh 10C 3.7V

3. 产品规格 SPECIFICATION（单颗电池规格 Specifications of single cell）

<table>
<thead>
<tr>
<th>测试项目</th>
<th>Test Project</th>
<th>单位</th>
<th>规格 Specification</th>
<th>条件 Condition</th>
<th>备注 Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>容量</td>
<td>Capacity</td>
<td>mAh</td>
<td>≥16800</td>
<td>标准充电后贮藏在</td>
<td>Up to 3 cycles are allowed</td>
</tr>
<tr>
<td>放电</td>
<td>Discharge</td>
<td>V</td>
<td>≥4.15</td>
<td>标准充电后1个小时内</td>
<td>≤2℃</td>
</tr>
<tr>
<td>现流率放电</td>
<td>High Rate Discharge (10C)</td>
<td>min</td>
<td>≥5.4</td>
<td>30℃时</td>
<td>≤3.0V</td>
</tr>
<tr>
<td>低温放电</td>
<td>Low Temperature Discharge</td>
<td>min</td>
<td>≥210</td>
<td>20℃±2℃环境中2小时</td>
<td>3.0V/cell</td>
</tr>
<tr>
<td>自放电</td>
<td>Charge Reserve</td>
<td>min</td>
<td>＞90%</td>
<td>标准充满后20度贮藏30天,</td>
<td>3.0V/cell Cut-off</td>
</tr>
<tr>
<td>寿命测试</td>
<td>Cycle Life Test</td>
<td>Cycle times</td>
<td>≥100</td>
<td>标准充满后10C放电至0.5C,</td>
<td>Re-tention capacity</td>
</tr>
<tr>
<td>短路测试</td>
<td>External Short Circuit</td>
<td>N/A</td>
<td>No Fire and No Explosion</td>
<td>Standard charge after short-circuit the cell at 20℃±5℃ until the cell temperature returns to ambient temperature (cross section of the wire or connector should be more than 0.75mm²)</td>
<td>≤ 80% of initial capacity</td>
</tr>
</tbody>
</table>
5.27.9. Trimming the setting of components (e.g. small adjustments of the pitch angle of the blades of a hydrofoil) whilst being installed and submerged in the water may be done both electrically and manually. Manual operation may be direct (manual operation of a control) or indirect (e.g. using a hydraulic or pneumatic system that is powered manually). The condition for manual operation is that there may be no significant propulsive force being generated from the manual operation of the system.

5.28 The configuration of the boat is not prescribed and may be adjusted throughout the race.

5.28.1. Any means to adjust the configuration must be electrically operated from the main battery.

5.28.2. It is not allowed to install a secondary power source for that purpose.

5.28.3. The adjustment of the solar panels may only be done electrically.

5.28.4. Furthermore, the boat must meet all requirements of these regulations in all possible configurations.

5.28.5. In Young Solar class boats only the position of the electric motor and the battery may be adjusted. They may be adjusted manually.

6. Solar panel

5.31 Sunlight is the only power source that shall be used for propulsion. Wind and human power are not allowed.

6.1.1. The sunlight may be used directly (received on board during the race using the solar panel) or may be stored in batteries or in other approved energy storage devices.

6.1.2. Batteries may be charged only from the solar panel during the race.

6.1.3. Batteries may be brought to the race fully charged.

5.32 The solar panels of the V20-class boats are standard to their particular class.

5.33 The solar panels of the Young Solar class boats are standard to their particular class.

5.34 The solar panel of A-class boats and Top-class boats must comprise of photovoltaic solar cells.

6.4.1. A-class boats may have a total combined exposed solar cell area as is given in the table below.

<table>
<thead>
<tr>
<th>PV cell chemistry</th>
<th>Allowable total cell area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>6.000</td>
</tr>
<tr>
<td>Thin film GaAs</td>
<td>5.328</td>
</tr>
<tr>
<td>Multijunction</td>
<td>4.000</td>
</tr>
</tbody>
</table>

6.4.2. Top-class boats may have a total combined exposed solar cell area as is given in the table below.

<table>
<thead>
<tr>
<th>PV cell chemistry</th>
<th>Allowable total cell area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>9.200</td>
</tr>
<tr>
<td>Thin film GaAs</td>
<td>8.170</td>
</tr>
<tr>
<td>Multijunction</td>
<td>6.133</td>
</tr>
</tbody>
</table>

6.4.3. The solar panel area will be determined by summing the total area of each solar cell from manufacturer’s data sheets. For the purposes of these regulations, the area of an uncut Sunpower cell having a width and length of 125 mm and diameter of 160 mm is 153.33 cm².

6.4.4. Areas of exposed bus bars, junctions and internal structures on top of the solar cell may not be deducted from the solar cell area.

5.35 The use of concentrators such as reflectors and/or lenses is not allowed.

5.36 The solar panels must be placed horizontally on all boats.

5.5.1.
6.6.1. The maximum deviation from the horizontal position is 10 degrees.
6.6.2. This also holds for the maximum deviation from the horizontal position of curved solar panels.
6.6.3. The use of adjustable solar panels is allowed provided they are adjusted by using (electrical) energy derived from the solar panels or the main battery.

6.7 Each applied solar panel must be mechanically secured to the boat, either in a frame or otherwise, and suitably protected against the influence of water.

6.7.1. The design of the fastening system must be such that it will be wind- and water resistant in all directions, including, turbulence, waves and gusts.
6.7.2. All parts of the solar panel sticking out of the hull as well as the frames used to attach the solar panels must be provided with protection of sharp edges.

5.3.7. Electronics

7.1. Participants are only allowed to use batteries that can be recharged electrically.

7.1.1. The use of other types of batteries, such as mechanically charged batteries is not allowed.
7.1.2. Every team is responsible for its own batteries.
7.1.3. All batteries cells used in the race must be commercially available.
7.1.4. The batteries may under no circumstances be modified in any way whatsoever.
7.1.5. The participants must disclose all data related to the batteries to the Organiser. The battery data provided must at least include a detailed description of the type of battery to be used and the so-called "materials safety data sheet" as supplied by the manufacturer thereby providing the organisation with adequate information in case of an emergency.

7.2. The batteries must be mounted in separate housings, such as to eliminate the risk of direct contact between the pilot and the batteries and environmental pollution is prohibited.

7.2.1. The purpose of the battery housing is to simplify the mounting of the battery in the boat.

7.2.2. The batteries and the fastening systems must be designed and manufactured such that they will remain fixed in their positions in the case of the boat capsizing and thereby prohibiting environmental pollution.
7.2.3. The battery housing may be a separate housing or may be fully integrated in the hull.
7.2.4. The battery housing must prohibit, in case of damage of the batteries, that electrolyte flows into the hull and/or into the environment.
7.2.5. The battery housing must be manufactured out of materials resistant to the electrolyte of the batteries.
7.2.6. The battery housing may not be made out of a galvanic conductive material.
7.2.7. The battery housing must be made out of a fire resistant material.
7.2.8. The attachment of the battery housing must be designed to withstand a 10 g acceleration or deceleration in any direction.
7.2.9. The use of Velcro for mounting the battery and/or its housing is not permitted.
7.2.10. The minimum distance between the batteries and the pilot is one metre. Young Solar class boats are exempted from this rule.
7.2.11. All requirements with respect to mounting the batteries and their housing also apply to all other means of energy storage.
7.2.12. The housing must be fitted with a forced ventilation system with a minimum capacity of 0.3 m³/minute. Young Solar Class boats are exempted from this rule.
7.2.13. Alternatively, the battery housing may be closed and cooled in another way (e.g. liquid cooling). In that case the cooling must be adequate for all expected circumstances of weather and power consumption.
7.2.14. In case of a battery failure gasses may never reach the compartment of the pilot.
7.2.15. The ventilation system must be operational at all times from the time the battery is electrically connected to the boat (= when the mains switch of the electrical system is on).
7.2.16. Both the inlet and the outlet of the ventilation system must be located in a position behind the pilot or in an alternative position that is suitably distant from the pilot; all subject to the sole discretion of the Organiser. The minimum distance required is one metre.

7.2.17. The battery ventilation system must be designed such that upward spray and rainwater will not be able to make direct electrical contact with the battery,

7.2.18. The battery ventilation system must be powered by the main battery and/or the solar panels.

7.3. The boats may be fitted with a battery pack with a maximum capacity given in rule 5.4 of these regulations. All further references to the battery pack will refer to the 'main battery'.

7.3.1. To be able to judge this requirement, all batteries will have to undergo a capacity test.

7.3.2. V20-class boats and Young Solar class boats are exempted from the capacity test.

7.3.3. All batteries tested and sealed in previous races are exempted from the capacity test.

7.4. For lithium based batteries this capacity test will be a constant resistance, full discharge test.

The resistance applied during the test is determined by the nominal voltage of the battery and given by the following expression:

\[ R_{\text{test}} = \frac{V_{\text{nom}}}{1500} \times (\pm 15\%) \]

Where: \( R_{\text{test}} = \) resistor value used during the test in Ohm

\( V_{\text{nom}} = \) nominal voltage of the battery in V

7.5. Teams using non-lithium based batteries must indicate this during the design procedure. An appropriate means of testing these batteries will be provided.

7.6. The starting point of the capacity test is a fully charged battery.

7.6.1. Fully charged is defined as the point where the individual cells have reached their maximum voltage and the battery pack as a whole is balanced.

7.6.2. The maximum cell voltages are:

<table>
<thead>
<tr>
<th>Type</th>
<th>Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium-ion</td>
<td>4.2 V ± 0.05 V</td>
</tr>
<tr>
<td>Lithium-Polymer</td>
<td>4.2 V ± 0.05 V</td>
</tr>
<tr>
<td>Lithium-Iron-Phosphate</td>
<td>3.6 V ± 0.05 V</td>
</tr>
</tbody>
</table>

7.6.3. A lead-based battery is considered fully charged when the voltage is 14.4 V for a 12 V nominal battery voltage and current through the battery has declined to less than 2% of the nominal capacity of the battery in Amp-hours (e.g. 2 Amps for a 100 Ah battery).

7.7. The end of the capacity test is when the battery is fully discharged.

7.7.1. Fully discharged is defined as the point where the discharge is stopped by the Battery Management System. This must be the point where all individual cells have reached a voltage below the value given:

<table>
<thead>
<tr>
<th>Type</th>
<th>Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium-ion</td>
<td>2.7 V ± 0.3 V</td>
</tr>
<tr>
<td>Lithium-Polymer</td>
<td>2.7 V ± 0.3 V</td>
</tr>
<tr>
<td>Lithium-Iron-Phosphate</td>
<td>2.5 V ± 0.3 V</td>
</tr>
</tbody>
</table>

7.7.2. A lead-based battery with a nominal voltage of 12 V is considered fully discharged when the voltage is 10.5 V. In order not to damage the battery during discharge the discharge will continue until the voltage reaches 11.7 V. At that time a depth of discharge of 70% is considered to have been reached. The full capacity will be calculated on the basis of that.

7.8. Only one battery pack per team can be offered for testing.

7.8.1. The battery pack offered must be balanced and have been fully cycled for at least 5 times.

7.8.2. The organisation does not take responsibility for incorrect functioning Battery Management Systems, unbalanced battery cells, and other kinds of failures of the battery pack that may appear during testing. These will also form no grounds for seeking redress.

7.9. A dedicated, properly functioning Battery Management System is mandatory for all batteries other than lead-acid and lead-gel batteries.

7.9.1. A solar controller is not allowed as a Battery Management System

7.9.2. The system must monitor both the battery’s voltage and temperature, and must also be capable of shutting the system down when necessary.
7.9.3. For Lithium-based batteries the monitoring of both charge and discharge currents is required. A means of controlling too high currents must be installed.

7.9.4. The Battery Management System must be designed to monitor all individual battery cells. A means to monitor the individual battery cell voltages must be provided and demonstrated during the battery test.

7.10. The maximum allowed system voltage is 52 VDC. The maximum allowed system voltage for Young Solar class boats is 30 VDC. However, a setup of the solar panels where the open circuit voltage is higher is acceptable under the following conditions:

7.10.1. When the electrical system is switched on (e.g. a maximum power point tracker or solar controller is active) the maximum voltage in the complete electrical system is 52 VDC or below or 30 VDC for Young Solar class boats.

7.10.2. In case the electrical system is switched off, the maximum voltage measured in the system is also 52 VDC, or 30 VDC for Young Solar class boats, with the exception of the part of the electrical system between the solar panels and the maximum power point tracker or solar controller.

7.10.3. In that part of the system and under that specific condition the maximum voltage must be 100 VDC or less or 50 VDC or less for Young Solar class boats.

7.10.4. The cabling and connectors used as well as the housing of the MPPTs will have to be of insulation class IP65 or higher. Possible cables can be of the type Ölflex solar XLS with Epic solar 4 connectors.

7.11. The maximum nominal allowed voltage of the (composed) main battery is 48 VDC.

7.11.1. In order to be able to comply with this rule in combination with rule 7.8 also during charging, the amount of batteries placed in series will be limited. The following limitations must be taken into account:

<table>
<thead>
<tr>
<th>Type of battery</th>
<th>Nominal voltage used</th>
<th>Maximum charge voltage</th>
<th>Maximum allowed number of batteries in series</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead-acid and lead-gel batteries</td>
<td>12 V</td>
<td>14.4 V</td>
<td>3</td>
</tr>
<tr>
<td>Nickel-Cadmium</td>
<td>1.2 V</td>
<td>1.5 V</td>
<td>34</td>
</tr>
<tr>
<td>Nickel-metal hydride</td>
<td>1.2 V</td>
<td>1.6 V</td>
<td>32</td>
</tr>
<tr>
<td>Standard Lithium-Ion</td>
<td>3.7 V</td>
<td>4.2 V</td>
<td>12</td>
</tr>
</tbody>
</table>

7.11.2. Young Solar class boats must install 2 12V batteries in series.

7.11.3. For the use of other types of batteries not mentioned in the overview the participant is required to contact the organisation to have determined the maximum allowed number of batteries in series.

7.12. It is not allowed for a team to install additional batteries at any given time, in any location in the boat and for any purpose with the following exemptions:

7.12.1. Hand held navigation and communication equipment powered by batteries is allowed as long as they are not electrically connected to the electrical system of the boat.

7.12.2. The use of (laptop) computers powered by batteries is allowed as long as they are not electrically connected to the electrical system of the boat.

7.13. All energy conducting parts must be fully insulated such as to prevent the occurrence of hazardous situations in the case of contact and exposure to water (for instructions on how to do this, please refer to the NEN/DIN standards for example). Special care has to be taken in case of boats made out of conducting materials (e.g. aluminium, carbon fibre, etc.).

7.14. The design of the electrical wiring and circuitry must be based on standard colour coding (NEN/DIN standards).

7.14.1. A plus-cable must be coloured or marked red.

7.14.2. A minus-cable must be coloured of marked black or blue.

7.14.3. All cables must be provided with a suitable strain relief.

7.15. All electrical cables must be properly sized to expected system currents. As a guideline the following table may be used. The table is based on continuous currents in a hot environment. It is the sole discretion of the Organiser to approve the cables used. For this they may divert from the values given in the table.

<table>
<thead>
<tr>
<th>Crosssectional area (mm²)</th>
<th>Allowed current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75</td>
<td>6</td>
</tr>
<tr>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>1.5</td>
<td>12</td>
</tr>
</tbody>
</table>
### 7.16. All boats must be fitted with an emergency mains switch that can simultaneously interrupt the power supply to the engine and the power between the solar panels and the Maximum Powerpoint Trackers / Solar Controllers in emergency situations. Thereby it isolates the power sources from the rest of the electrical system. This switch is not the same switch as the dead man’s switch

#### 7.16.1. The switch must be capable of breaking the electrical power supply under full load.

#### 7.16.2. The switch must be accessible for emergency personnel from the outside of the cabin. It’s position must be marked clearly on the outside of the boat such that the switch can be easily located.

#### 7.16.3. The switch must be clearly marked as an emergency switch.

#### 7.16.4. The switch must be operated via a red coloured ‘mushroom’ type push button

#### 7.16.5. The ‘on’ and ‘off’ positions must be clearly displayed.

#### 7.16.6. The lettering must be of a minimum height of 20 mm.

#### 7.16.7. It is allowed to use one or more relays in the switching system.

#### 7.16.8. In the case of the use of a relay or contactor, this relay/contactor must be rated for the application.

#### 7.16.9. A system that short circuits the solar panels will be allowed for interrupting the current to the MPPTs / solar controller.

### 7.17. All electrical systems must be provided with a fuse in serial connection with the main battery (‘main fuse’).

#### 7.17.1. The main fuse may under no circumstances carry more than 200% of the expected power.

#### 7.17.2. The main fuse must be mounted as close as possible to the main battery.

#### 7.17.3. The rating of the main fuse may not be higher than the allowed current in the thinnest wire in the relevant part of the electrical system.

#### 7.17.4. In addition to the main fuse, as a minimum, the following systems must be fused:

- Solar panel
- Motor controller
- Battery
- Battery Management System

### 7.18. Participants are bound to use eye-protecting eye gear at all times when assembling, mounting and/or relocating the batteries and/or when performing any other types of activities related to the batteries.

#### 7.19. It must be possible to easily seal the energy storage system(s) (battery or any other type of energy storage).

#### 7.19.1. The participating teams must make sure that the necessary means are made available such that the organisation can apply the seal in a simple and fast way.

#### 7.19.2. The Organiser will apply the seal after the boat has been technically approved.

#### 7.19.3. If a participant needs to break the seal, he or she is bound to notify the organization as soon as possible.

#### 7.19.4. The boat is prohibited from racing from the moment the seal has been broken.

#### 7.19.5. The boat may only return to the race once it has been subjected to a technical re-inspection and a new seal has been installed.

#### 7.19.6. It must be possible to easily seal the housing. This must be done in such a way that it is not possible to (re)charge the battery with any other source than solar energy and that it is not possible to replace the battery without breaking the seal.

#### 7.20. During the technical inspections and/or at any moment on request, the teams are obliged to show the electrical circuitry schemes.