Effect of the Inclusion of Photovoltaic Solar Panels in the Autonomy of UAVs Time of Flight

Joana Filipa Silva Engana do Carmo

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Supervisors: Professor João Paulo Neto Torres
Capitão Engenheiro Gonçalo Cruz

Examination Committee

Chairperson: Professor Francisco André Corrêa Alegria
Supervisor: Professor João Paulo Neto Torres
Member of the Committee: Professor Carlos Alberto Ferreira Fernandes

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The present work comes from a partnership between Instituto Superior Técnico, Military Academy and Centro de Investigação da Academia da Força Aérea (CIAFA) and I would like to thank CIAFA additionally, for providing me the vehicle related data giving me the means to complete this mater thesis.

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Abstract

Photovoltaic technology and unmanned aerial vehicles are both alluring areas with a lot of potential to explore. Consequently, it allows them an ability to adapt and progress when faced with new challenges, hence their wide range of applications. An auspicious combination between the two is born from the UAVs’ inability to overcome some of its problems, namely the autonomy one. This master thesis springs from the need to vanquish the problem, finding a more permanent solution. Its aim consists in the installation solar photovoltaic panels in the structure of an UAV, with the objective of studying its influence on the vehicle's time of flight. To accomplish it, a theoretical study will be made, encompassing all the potential variables together with its influence. In order to verify the credibility of this claims, a prototype, based on the original aerial vehicle structure form and material, is constructed, using COMSOL Multiphysics. Later, the prototype will be used to evaluate possible harsh circumambient air to structure interactions, modeled by the fluid motion describer Navier-Stokes equations. For a smooth approach involving lighter computational power, a RANS model is going to be used to assess the equations. Based on its results the chosen solar technology credibility will be evaluated. Solar cell's simulations will also be made, accepting as input previously studied parameters which will modify its performance. Bearing in mind the produced results, it is concluded that the solar panels can only augment significantly the time of flight on very specific conditions.

Keywords

Autonomy; Photovoltaic Technology; Solar Cell; Time of Flight; Unmanned Aerial Vehicles.
Resumo

Veículos aéreos não tripulados - do inglês Unmanned Aerial Vehicle (UAV) - e tecnologia fotovoltaica, são ambas áreas vistas como atraentes com muito potencial por explorar. Consequentemente, esse potencial propicia-lhes uma grande capacidade de adaptação quando confrontadas com novos desafios, sendo daí originada a sua variedade de aplicações. Uma vantajosa combinação entre as duas nasce da falta de capacidade dos UAVs de ultrapassar alguns dos seus problemas, nomeadamente a autonomia. Esta tese de mestrado advém da necessidade de eliminar o problema, encontrando uma solução de certo modo permanente. O seu objetivo consiste na instalação de painéis solares fotovoltaicos na estrutura do UAV com o intuito de estudar a sua influência no tempo de voo do veículo. Para o realizar, um estudo teórico vai ser feito, abrangendo todas as potenciais variáveis, junto com a sua influência. De modo a verificar a credibilidade das reivindicações, um protótipo baseado na forma da estrutura e material do veículo original é construído com recurso ao COMSOL Multiphysics. Mais tarde este será usado para avaliar possíveis efeitos drásticos das interações entre o ar envolvente e a estrutura, que serão representadas pelas equações modeladoras de fluidos, Navier-Stokes. Para uma mais fácil abordagem, ou seja, envolvendo menos poder computacional, o modelo RANS - do inglês Reynolds averaged Navier-Stokes -, vai ser usado de forma a aferir melhor as equações. Baseado nos resultados obtidos, a credibilidade da tecnologia solar escolhida irá ser avaliada. Simulações com as células solares vão também ser feitas, aceitando como entrada os parâmetros previamente estudados e que irão modificar a sua operação. Tendo em consideração os resultados obtidos, conclui-se que os painéis solares só conseguem aumentar significativamente o tempo de voo em condições muito específicas.

Palavras Chave

Autonomia; Célula Solar; Tecnologia Fotovoltaica; Tempo de voo; Veículo Aéreo não Tripulado.
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Acronyms

ABL  Atmospheric Boundary Layer
AC  Alternating Current
AOA  Angle of Attack
BIPV  Building Integrated Photovoltaics
CIAFA  Centro de Investigação da Academia da Força Aérea
CIGS  Cooper Indium Gallium Diselenide
CS  Control Station
CdTe  Cadmium Telluride
CZTS  Cooper Zinc Tin Sulfide
D3  Dull, Dirty and Dangerous
DC  Direct Current
DSSC  Dye-Sensitized Solar Cell
ECMWF  European Center for Medium-Range Weather Forecasts
EHP  Electron-Hole Pair
ESPAR  Electrically Steerable Passive Array Radiator
GHI  Global Horizontal Irradiance
GPS  Global Positioning System
ISR  Intelligence, Surveillance and Reconnaissance
IST  Instituto Superior Técnico
MJ Multijunction
MPPT Maximum Power Point Tracker
NOCT Nominal Operating Cell Temperature
OSC Organic Solar Cell
PCE Power-Conversion Efficiency
PSP Perovskite Solar Paint
PSK Phase Shift-Keying
PV Photovoltaic
QD Quantum Dot
QDSC Quantum Dot Solar Cell
QDSP Quantum Dot Solar Paint
RANS Reynolds-Averaged Navier-Stokes
RPA Remoted Piloted Aircraft
SP Solar Paint
SPH Solar Paint Hydrogen
STC Standard Test Conditions
US Unmanned System
UV Unmanned Vehicle
UAV Unmanned Aerial Vehicle
UGV Unmanned Ground Vehicle
UMA Unmanned Air Vehicle
USB Universal Serial Bus
USV Unmanned Surface Vehicle
UUV Unmanned Underwater Vehicle
## Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tr>
<td>$A$</td>
<td>Area</td>
</tr>
<tr>
<td>$AM$</td>
<td>Air mass</td>
</tr>
<tr>
<td>a-Si:H</td>
<td>Hydrogenated amorphous Silicon</td>
</tr>
<tr>
<td>$c$</td>
<td>Velocity of light in the vacuum</td>
</tr>
<tr>
<td>CdTe</td>
<td>Cadmium Telluride</td>
</tr>
<tr>
<td>c-Si</td>
<td>Crystalline Silicon</td>
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<tr>
<td>$E$</td>
<td>Young’s Modulus</td>
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<tr>
<td>$E_g$</td>
<td>Bandgap energy</td>
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<tr>
<td>$E_{ph}$</td>
<td>Photon energy</td>
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<tr>
<td>$F$</td>
<td>External forces</td>
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<tr>
<td>$FF$</td>
<td>Solar cell’s fill factor</td>
</tr>
<tr>
<td>$g$</td>
<td>Gravitational acceleration constant</td>
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<tr>
<td>GaAs</td>
<td>Gallium Arsenide</td>
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<tr>
<td>$H_0$</td>
<td>Reference Irradiance</td>
</tr>
<tr>
<td>$H_d$</td>
<td>Direct Radiation</td>
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<tr>
<td>$h$</td>
<td>Constant of Planck</td>
</tr>
<tr>
<td>$h_0$</td>
<td>Height at the bottom of atmospheric layer</td>
</tr>
<tr>
<td>$h_s$</td>
<td>Height about sea level</td>
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<tr>
<td>$h_w$</td>
<td>Wind convection coefficient</td>
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</table>
\( h_{\text{w,NOCT}} \) Wind convection coefficient under NOCT conditions

\( I \) In plane irradiance

\( I_{\text{mp}} \) Current at maximum power

\( I_{\text{sc}} \) Short circuit current

\( k \) Fluid turbulent kinetic energy

Li-Po Lithium Polymer

\( M \) Molar mass of Earth’s air

\( N_A \) Density of the negative charged acceptor ions

\( N_D \) Density of the positive charged donor ions

\( n_c \) Solar cell unit vector

\( n_i \) Intrinsic concentration

\( n_s \) Solar unit vector direction

\( P_0 \) Pressure at sea level

\( P_{\text{in}} \) Incident power

\( P_{\text{hs}} \) Pressure at the desired height relatively to sea level

\( p \) Fluid pressure

\( R \) Universal gas constant

\( R_{\text{series}} \) Solar cell’s series resistance

\( R_{\text{sh}} \) Solar cell’s shunt resistance

\( r \) Radius of curvature of the Flexible Silicon solar cell

\( T_a \) Ambient temperature

\( T_{a,\text{NOCT}} \) Ambient temperature under NOCT conditions

\( T_{\text{hs}} \) Temperature at the desired height

\( T_{\text{NOCT}} \) Nominal operating cell temperature under NOCT conditions

\( T_{\text{STC}} \) Ambient temperature under STC

xx
Thickness of the Silicon

Flow velocity

Flow velocity time averaged component

Flow velocity turbulent fluctuating component

Built-in potential

Voltage at maximum power

Open circuit voltage

Thermal voltage at room temperature

Velocity of wind at the anemometer height

Velocity of wind at the desired height

Width of the N-side of the depletion layer

Width of the P-side of the depletion layer

Surface roughness length

Anemometer height

Desired height

Absorption coefficient of the cells

Temperature coefficient of maximal power under STC

Efficiency of the solar cell or panel

Efficiency under STC

Angle of incidence of the radiation on the solar cell’s surface

Zenith angle

Fluid dynamic viscosity

Fluid turbulent viscosity

Density of the fluid

Tensile yield strength
$\tau$ Transmittance of the cover system

$\varphi$ Azimuth angle
Introduction

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1.1 Motivation

The end of the 20th century and the beginning of the 21st were marked by a quick evolution which has made the technologies foster, stating its influence in the widest areas. Aviation is one of those areas and due to its demand for the most varied applications, it is in constant development striving to keep up with the technological advances, both in terms of equipment and solutions.

The main drive behind the aircraft development was always the human being's desire of a fast and safe transportation of people and cargo [1]. However, the advantages of possessing "flying machines" were soon recognised by the military, who could benefit greatly by possessing the upper hand in confrontations, or avoiding them, with resource to aerial weapons and recognisance of enemy forces and fields of action, in order to enable anticipation as well as informed decisions. Nevertheless, risks for human life were still present in evaluating terrain by air.

Around the time of the First World War, 1916, the first Unmanned Aerial Vehicles (UAVs) appeared, once again with the primary application being the military one, solving gradually, as the air-crafting was enhanced, the problems of the D3 - Dull, Dirty and Dangerous - missions. UAVs started blooming for other applications - such as environmental monitoring and incident analysis -, at the birth of the 21st century and its use is still growing at current times for the most varied purposes.

UAVs are still raw in terms of potential for they carry many issues which currently have no ultimate solution and that can affect negatively their performances, making them unreliable in some cases. Example of this are the problems with improved autonomy, man-machine interfaces, communications, range and its ineptitude to consistently recognise and avoid other aerial systems and objects.

The research object of this master thesis is centered around one of the problems announced before, more specifically, the improved autonomy of UAVs. Currently, there are many efforts trying to progress in order to achieve a relatively general solution to make these vehicles reliable in terms of energy for a long term usage, guaranteeing without fail, that key aspects of the UAVs operation are not compromised. The utilization of photovoltaic solar panels is heavily weighted, as it is a growing field and the conversion of energy from solar to electrical is highly appealing due to its green and self-sustainable natures.

Solar panels were created by Charles Fritts in mid 1880s and were considered by the inventor a way to revolutionize the energy production and the related pollution [2]. From its birth to current times, solar technology keeps evolving and adapting to the consumer needs, taking into particular consideration the resonating factor: its efficiency. Although its importance is unquestionable, the UAVs have, as aforementioned, aspects that can not be discredited, being them the shape - that can not be altered -, and the weight - which can fluctuate fairly from the original value. Therefore, a combination of the UAV and photovoltaic technologies can be considered challenging, for the conditions must be fulfilled and the efficiency ought to be enough to ensure a significant augment of the time of flight.
1.2 Objectives

This study comes from a partnership between Instituto Superior Técnico, Military Academy and Centro de Investigação da Academia da Força Aérea (CIAPA). It inserts itself in the sequence of a master thesis by António Fernando Alves Carneiro, titled “'Smart’ antena para aplicação em UAVs”, which tried to solve the problems of communications and range in UAVs, aforementioned. A trial and a control system were made for an Electrically Steerable Passive Array Radiator (ESPAR) antenna composed by two different antennas: an unidirectional monopole quarter wavelength, with Phase Shift-Keying (PSK) modulation and a bandwidth of 8.7 MHz and a patch directive antenna with frequency 1.33 GHz. This system maximizes the received and sent signals by “changing the azimuth direction of the radiation lobe, that is accomplished by varying the coupling between the aggregate elements” [3].

The present research aims to solve another of the enunciated problems, the autonomy, by the augment of the time of flight. This will be achieved including thin film photovoltaic solar panels wrapped around the UAV structure, so that solar energy can be used to charge the vehicle’s batteries. Various solar technologies will be presented and the most appropriate selected. A theoretical study of the system influencing variables is expected to be made, as well as later simulations of the UAV system and panels, that consider the researched and relevant information. The solar cells are also to be tested and the results recorded. Ideally, the resulting electrical energy from the implemented panels will be able to increase considerably the time of flight, taking a further step into turning the photovoltaic technology a viable, and perhaps definite, solution to the improved autonomy problem.

Taking into consideration the previously referred points necessary to cover in this master thesis and taking into account the theoretical and simulated components needed, the order of works that composes the objectives of this study will be:

- Description of the UAVs and solar technologies;
- Choosing of the most appropriate technology;
- Theoretical study of some variables that can affect the UAV surface and the cells;
- Development of an UAV prototype and simulation of the studied variables effect with resource to it;
- Study of the solar cells output with the conditioning variables;
- Taking conclusions about the influence of the solar panels on UAV time of flight.
1.3 Outline

The current work is divided into seven prime chapters. This first chapter is basically an introduction to the objects of study containing the motivation behind the topics and the fixed objectives. The second and third chapters cover an overview in the UAVs and solar photovoltaic technology. A particular focus on the cells mode of operation and its available technologies is given by the third chapter. On the fourth chapter, the state of the art is presented, featuring a more detailed view of the problem description, followed by a study of the influencing variables and data collecting. Fifth chapter contains the explanation concerning the UAV prototype construction and the consequent COMSOL Multiphysics simulations with resource to it. Sixth chapter also uses COMSOL Multiphysics simulations, this time, to evaluate the solar cell operation. The previously theoretically researched variables will be used as an input. With resource to the solar cell simulations, photovoltaic panels will be constructed and its output energy accounted. Finally, seventh chapter contains this works’ conclusions as well as some indications for possible future works.
Unmanned Aerial Vehicle Overview

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When the term “Unmanned Aerial Vehicle” arises, an association with a military vehicle is almost instantly made. Although it was true by the time of its creation, UAVs have evolved and nowadays have common civilian uses, for instance photographs or movie making, enabling the capture from different angles and heights. However, depending on its application, factors like the size, weight and power are varied, in order that a machine with adequate levels of reliability, strength and hardiness can be built [1].

As one of the central points of this thesis are the UAVs, the next chapter is centered on them. A brief approach will be made on its background and an explanation about its concept, functions and problems is going to be done.

2.1 Unmanned Aircraft Background

The first recorded autonomous flying machine, also known as “the pigeon”, a mechanical bird made of wood, was built around 425 BC by Archytas, the Tarantine. Reports state that it flew about 200 m before collapsing to the ground [1]. For the era the invention was considered a breakthrough, as the discovery of the skies, with the technologies at hand, was no more than a dream. Several centuries later, in 1783, the first manned flight using hot air balloons occurred. Balloons dominated the aircraft until helicopters took its place in the 1860s.

Nikolai Tesla, in 1884, created the first written plans for a remotely controlled unmanned airplane with his revolutionary idea for electric power transmission with Alternating Current (AC) over long distances. According to his claims, the machine in cause would change its direction in flight and explode, when commanded, and never miss. Tesla’s work in investigation continued, however was mostly discredited and never pursued further than a few tests with the investment of the United States Navy [4].

Soon after, the advent of the airplane followed, more precisely in 1903 by the Wright brothers. The airplanes breakthrough and the First World War triggered the interest of the military in aircraft and the benefits of a flying machine without a pilot on board stood out. Both the Navy and the Army focused more in experimenting with the already existent machines, for example aerial torpedoes and flying bombs, in order to develop the unmanned aviation. Investments were made and in 1916 it payed back with the first modern UAV the Hewitt-Sperry Automatic Airplane [1,5].

In the 20th century, aviation continued to develop hand-in-hand with technology. Manned aircraft grew almost exponentially as its numbers went from a few hundred machines to tens of thousands. Notwithstanding, unmanned aircraft was more or less put into a halt, as the required technologies - automatic stabilization, remote control and autonomous navigation -, were considered not mature enough [4].

At the threshold of a new century - 1990s -, the birth of the information era occurred, signaled by a technological boom. The emergence of the Global Positioning System (GPS) and the satellite communications enabled the UAVs’ development by presenting a solution to the remote control and
autonomous navigation problems. The continuous growth in the technological sector led to a general progression of the UAVs, being it in terms of design, components or capacities, until they reached the present point of evolution.

To better accentuate its progression, in figure 2.1 three UAVs from different times are shown. In figure 2.1(a) a sketch, drawn as close to reality as the reports allow, of Tarantine’s aerodynamic pigeon is presented. Separated from it by more than two millenniums, in figure 2.1(b) the Hewitt-Sperry Automatic Airplane, also known as the “Flying Bomb”, can be seen. Lastly, figure 2.1(c) shows an example of a nowadays used UAV and although the time span between it and figure’s 2.1(b) UAV is shorter, the technological difference can clearly be seen at naked eye.

(a) Flying Pigeon (from [1]). (b) Hewitt-Sperry Automatic Airplane (from [6]). (c) Modern UAV (from [7]).

Figure 2.1: Evolution of the UAVs along time.

2.2 Introduction of the Unmanned Aerial Vehicles

Unmanned Aerial Vehicle (UAV), Remoted Piloted Aircraft (RPA) or Unmanned Air Vehicle (UMA) are some of several ways to reference the same object. UAV as it is more frequently called, is a powered aerial vehicle that does not carry an onboard human pilot or passenger, is capable of flight remotely piloted or autonomously and can be expendable or recoverable [1,8]. An UAV can also carry harmful or non-harmful payloads and as a consequence of the first, being mistaken by guided weapons. However the differences lie in the term "recoverable", since munition delivery systems are considered expendable and a single UAV is able to perform a variety of missions. While the munitions for the UAV are a simple payload, for the guided weapons they are part of the aircraft structure that can’t be removed.

UAVs are a sub-category of a wider one, known as Unmanned Vehicles (UVs) in which are included vehicles deployed bellow water levels - Unmanned Underwater Vehicle (UUV) -, at the sea surface - Unmanned Surface Vehicle (USV) -, in air - the previously mentioned UAV -, [9] and at land - Unmanned Ground Vehicle (UGV). All the above UVs, are part of an Unmanned System (US), which is composed by the succeeding sub-systems [10,11]:
• The aircraft and respective payload;

• A Control Station (CS) and often other remote stations containing the interfaces between human and machine;

• The communication system, responsible for the exchange of information between CS and UAV;

• Support equipment which comprises maintenance and transport items, and for UAVs aircraft launch and recovery;

• A human element, key factor to a successful employment by ensuring the prerequisites and interface during the mission.

In the modern world, the demands for UAVs are increasing. Although nowadays the aerial vehicles are still used for military purposes, its operation areas have extended far beyond that. UAVs are divided in three classes: military target aircraft, used for training purposes; Intelligence, Surveillance and Reconnaissance (ISR) data gathering aircraft which can be used for the most varied tasks, for example agriculture monitoring, pollution and land monitoring, fire detection, incident investigation, etc, and combat aerial vehicles [5,10,12].

Despite providing a lot of benefits, the aerial vehicles still have some problems, currently unhanded, that can consequently undermine the fulfillment of its mission and result in potential risks for the machine and its surroundings. Man-machine interfaces, communications and range still lack an ultimate solution and when one of the first enunciated fails the UAV could lose control, risking damage of property or injuring people. They also have an ineptitude to consistently recognise and avoid other aerial systems and objects, adding to the danger list a potential collision with manned aircraft.

The unmanned aircraft also lacks in its performance in terms of power. Completing a task may be put on hold by the sheer necessity of recharging or substitution from the vehicle which could every so often undermine or even foul up the task. This problem could be solved by increasing the size or the number of batteries of the UAV however, considering that the flight time of the vehicle is inversely proportional to the weight, the batteries need to be a compromise between the gained power and the additional weight. In sum, the reported complication isn’t so easily solved as the UAV has substantial weight restrictions. Up-to-date, the most appealing solution consists in the inclusion of solar cells in the UAV structure, enabling the collection of solar energy to increase the time of flight [13].

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3

Solar Photovoltaic Panels
Presentation

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Energy requirement is predicted to grow globally with the bulk demand from the developing countries. Energy consumption is expected to double by the middle of this century, increasing the need to invest in energetic sources that can be replenished on a human timescale. Renewable energies are energies that come from natural sources or constantly rechargeable processes - such as sun, wind and water. They are expected to cover, in the long term, the additional power necessity [2].

Solar photovoltaics (PVs) is currently the largest renewable employer, and will be the one used in this study. Its operation principle is based in the conversion of solar radiation into Direct Current (DC) electricity by incidence of sunlight in a solar cell. According to this, the following chapter will focus on the solar cell, namely its history, types and how it works.

### 3.1 Solar Cell History

In 1839, Alexandre-Edmond Becquerel found the means for transforming solar to electrical energy by discovering the Photovoltaic Effect, or Becquerel Effect. The physicist used an electrochemical cell composed by two similar platinum, gold, brass or silver plates submerged in an acid, neutral or alkaline solution and illuminated one of the two, observing by result of his action, the production of an electric current [14–16].

The first solar cell was made in 1883, New York, by Charles Fritts, as he coated the semiconductor selenium with a transparent layer of electricity conductor, gold in his case. Comparing his cell with the other inventors previous attempts Fritts claimed his cell worked because he ensured the two selenium parts, where the current enters and exits, were put under different electric potentials so that the two forces acting upon selenium would not neutralize each other [17]. Despite his success, the cells’ efficiency was considerably low, around 1%, making it not viable.

Until the 1940s, the more efficient cells used Se, Cu$_2$O, or Tl$_2$S. By the understanding of the P-N junction, Russell Ohl, in 1941, produced the first silicon modern solar cell by the doping of the pure semiconductor [18]. As the efficiency was considered extremely low, the cells had no practical use. Only in 1954, with the achievement of silicon crystals pure enough, by Calvin Fuller, the silicon cells efficiency was considered good enough for practical use (around 5%) [16].

From the birth to the actual times, solar cells improved drastically and continue to do so, either in terms of efficiency, reliability, fabrication techniques or materials. It is said that “the PV field is moving so quickly that by the time information appears in print, it is generally outdated” [19]. Nowadays, solar technology is more commonly produced and used in the form of photovoltaic solar panels or modules, which is the connected assembly of solar cells.
3.2 Brief Insight on Semiconductors

Semiconductors are the solar cell base. These materials are classified by its electrical conductivity, which inserts itself between the values of an insulator and a conductor. However, it is important to emphasize that semiconductor's resistance is a variable value with inverse dependence on the temperature: as the temperature rises the resistance decreases and vice-versa.

Semiconductors can be divided in two types: intrinsic and extrinsic. Intrinsic semiconductor is considered the pure form, for at an absolute zero temperature its valence band is completely filled and the conduction band completely empty and this way having all the covalent bonds completed. If impurities are added (doping) an extrinsic semiconductor is born. Compared to the intrinsic ones, this semiconductors have more electrons or holes and consequently either its conduction or valence band are closer to the Fermi level, making them more conductive at a minor temperature.

Based on the type of added impurities, extrinsic semiconductors may be classified as N-type or P-type. The addition of pentavalent or donor impurities contributes with free electrons to the semiconductor, creating a N-type, which compared to the intrinsic semiconductor has a higher conductivity. A P-type is created by the addition of trivalent or acceptor impurities to the intrinsic semiconductor, which results in the deficiency of valence electrons, commonly called holes.

Between the conduction and a valence band of a semiconductor exists an energy state where no electrons can be. This energy state is called bandgap and its known by the difference of energies between the valence and the conduction band. Furthermore, semiconductors can be classified according to its momentum bandgaps. If the momentum of charge carriers is the same in conduction band and valence band, a semiconductor is said to have a direct bandgap. However, if the previous condition is not verified, the semiconductor will have an indirect bandgap. When the semiconductor has a direct bandgap it tends to have better light absorption properties, as a change in momentum isn’t necessary for the excited electron.

3.3 The P-N Junction Operation

As it was previously stated, solar cells are composed by two types of semiconductors, a N-type and a P-type that in its contact form a P-N junction. When the semiconductors are first joined, a large density gradient is present between the two sides, resulting in the diffusion of electrons from the N-type to the P-type. These will combine with the in-there existent holes producing along the junction a negative charged acceptor ions with density $N_A$. The holes in the P-type will also diffuse to the N-type, combining with the electrons and producing along the junction positive charged donor ions with density $N_D$.

An equilibrium is reached with the creation of an electric field from the N-type to the P-type caused by the presence of impurity ions. It will act as a "barrier" around the area of the junction, opposing the
diffusion for both electrons and holes, as the negative charges (electrons) are repelled to the opposite direction of the electric field and the positive charges (holes) are attracted. This area in the vicinity of the junction is called the depletion layer. It has width, $W$, given by sum of $W_N$ (width of the N side) and $W_P$ (width of the P side) which relate according to equation 3.1 obtained by setting the values of the electric fields at both sides equal to each other in the boundary. Equation 3.1 states that the total charges of the two sides of the junction must have the same value.

$$W_P \times N_A = W_N \times N_D$$  \hspace{1cm} (3.1)

Across the junction there is an electrostatic potential difference, $V_b$ (built-in potential) even without an external applied voltage, that can be given by the equation 3.2 that expresses the difference between the work functions of the two sides, where $V_T$ is the thermal voltage at room temperature and $n_i^2$ is the intrinsic concentration [20].

$$V_b = V_T \ln \frac{N_D \times N_A}{n_i^2}$$  \hspace{1cm} (3.2)

### 3.4 Photovoltaic Effect

Photovoltaic effect consists in a chemical and physical phenomenon that by reacting to the light, generates a voltage and a current across a device - mostly solar cells. Photoelectric effect is in several aspects related to the photovoltaic effect, even so, while in the first the excitation of an electron results in its ejection from the material, in the later it only traduces in a passage between the semiconductor bands.

Light is composed of photons whose energy is inversely proportional to the photon's wavelength ($\lambda$), as shown in equation 3.3. For the photovoltaic effect to occur the incident photon's energy must equal or exceed the semiconductor’s bandgap energy, $E_g$. If the condition is verified the photon will be absorbed by the semiconductor, giving to electrons the required energy to transpose from the valence band to the conduction band. With the electron’s transition a hole is always created in the valence band, as such when the phenomenon occurs it can be said that Electron-Hole Pairs (EHPs), with number proportional to light’s intensity, are established. When the photon’s energy is higher than the energy required to excite the electrons, the remaining energy will be dissipated as heat, warming up the solar cell and thus lowering the efficiency.

$$E_{ph} = \frac{hc}{\lambda}$$  \hspace{1cm} (3.3)

The EHP behaviour strongly depends on its region of emergence. Case the photon is adsorbed
inside the depletion layer of the junction, the electric field will cause the movement of the electrons to the N-type side and the holes to the P-type side. If the two semiconductors are short circuited the carriers will exit the device as photogenerated current with direct proportionality to the irradiation of the incident light. In the absence of the short circuit a diminish of the existent electric field will be caused therefore increasing the diffusion. A new equilibrium will need to be reached.

Case the EHP is generated in the vicinity of junction, in the radius of a diffusion length from the depletion region, it will contribute to the photogenerated current before a recombination happens and behave itself in the same manner as if the EHP was created inside the junction. For a photon absorbed far from the junction, with far being a distance bigger than a diffusion length and as such a recombination will happen before the EHP can reach an electrode. The excited electron will return to its orbital dissipating energy as heat and subsequently decreasing the cell's efficiency [20].

3.5 Generations of Photovoltaic Technologies

Solar cells are in general divided in three generations in accordance with the period of invention, objective to be accomplished, material used and method of fabrication [21]. The generations and its most prominent solar cells are presented in figure 3.1.

![Figure 3.1: Generations of PV technologies and its cells.](image-url)
3.5.1 First Generation Solar Cells

Wafer based or first generation solar cells were the pioneers of the photovoltaic technology and are, since then, leading the market. Its name derives from its fabrication method which consists in the creation of slices - or wafers - of the semiconductor material. This generation is composed by three types of cells: Crystalline Silicon (c-Si), Gallium Arsenide (GaAs) and III-V Multijunction (MJ).

- Crystalline silicon (c-Si) is the photovoltaic technology with the largest market share - with the cause of its 90% quota being assigned to the abundance of silicon as resource -, and the highest Power-Conversion Efficiency (PCE), up to date. However, c-Si solar cells are associated with high production costs, when compared to other cells, due to its long-lasting manufacture and its complex structures. Reducing the cell's thickness is an important aspect to cost reduction.

  c-Si cells can be monocrystalline, made from a single continuous crystal silicon formed into bars and cut into wafers. As the electrons have more space to move the panels are more efficient and as of consequence more expensive. Nowadays its PCE is 26.4%, close to the theoretical limit of 29.4%. They can also be polycrystalline, made into wafers by the melting of many silicon crystals together. They have more minority carrier recombination due to it's high impurity densities and as such have lower efficiencies (23.3%) and prices, turning them more appealing to the market [22].

- Gallium Arsenide (GaAs) solar cells, when compared to silicon have many properties that make them highly attractive. It has a high bandgap energy, which traduces in a low temperature coefficient and a good weak illumination performance. It also has a high saturated electron velocity and mobility, allowing them to travel a longer distance without recombining. The presented properties traduce themselves in a high efficiency (29.1%), which permits the creation of thin lightweight cells with a relatively good flexibility. The advantages come with the price of a high cost.

- III-V Multijunction (MJ) or tandem cells are cells that contain several p-n junctions of different semiconductors in groups III and V of the periodic table. Having different materials enables the existence of different bandgap values making possible the absorption of photons with different wavelengths and therefore captures a wider spectrum of energy that would be dissipated as heat in a single cell. Due to the previously described, MJ cells are the most efficient - highest achieved was 47.1% with four junctions or more -, making them appealing for operation even over low irradiation. Nevertheless, MJ cells have a small market share, since the costs are high and the margin for the composites cost reduction is small [23].
3.5.2 Second Generation Solar Cells

Thin-film or second generation solar cells are made by the deposit of thin layers of PV material over a substrate. This technology focused its efforts in producing flexible and weightless cells, with thickness from nanometers to micrometers, they are easier to be adapted to various surfaces [21]. Compared to first generation, thin-films have the disadvantage of lower efficiency but the great advantage of a lower cost due to its simplicity of manufacturing.

Second generation photovoltaics is composed by five cells: Cadmium Telluride (CdTe), Cooper Indium Gallium Diselenide (CIGS), Cooper Zinc Tin Sulfide (CZTS), Hydrogenated Amorphous Silicon (a-Si:H) and Flexible Silicon.

- Despite having cadmium (toxic heavy metal), cadmium telluride (CdTe) solar cells are not an environmental concern seeing that at the end of its life the modules are recycled. CdTe has the shortest energy payback time of the available PV technologies with values of 0.42 years for the module [24], lower costs than c-Si cells in multi-kW systems and an efficiency (22.1%) similar to polycrystalline silicon cells. These characteristics make CdTe technologies attractive for large photovoltaic power stations.

- CIGS is a semiconductor composed of copper, indium, gallium and selenium. CIGS solar sells are mostly produced with the thermal evaporation method and thereby have an efficiency (23.4%) similar to that of polycrystalline silicon. Like CdTe it also has toxic materials in its composition. With its direct bandgap and high absorption coefficient, CIGS cells can afford to have a thickness in the order of microns and therefore be deposited on flexible substrates requiring few materials. The result will be modules with broad applications, such as in Building Integrated Photovoltaics (BIPV). Counterbalancing the good points CIGS cells strive to reach a perfect integration of its large combination of materials and control its impurities [25].

- CZTS is a quaternary semiconductor like CIGS in which indium and gallium are replaced by zinc and tin - abundant and non-toxic elements. Resembling the other quaternary solar cell, CZTS has high carrier concentrations and absorption coefficient permitting the fabrication of thin solar cells that can be made flexible and adaptable. CZTS cells pay the price for its non-toxic materials with a low PCE (12.6%) when compared to CIGS and CdTe.

- Hydrogenated Amorphous Silicon (a-Si:H) solar cells were born by adding hydrogen during fabrication process of unhydrogenated a-Si, improving the poor conductivity and the high defect density problems of a-Si, and making the doping of the solar cell possible. Notwithstanding a-Si:H still has efficiency problems affecting its performance due to Staebler-Wronski effect - creation of defects.
by extended illumination of the cell that decreases photoconductivity -, that need to be overcame for a good operation [26]. Due to the pointed problems the PCE of this cells remains around 14%.

- Crystalline silicon, the present preferred material on wafer-based solar cells, is also very appealing to thin-film solar cells. This desire originated the creation of Flexible Thin Crystalline Silicon solar cells, commonly referred as Flexible Silicon solar cells, which derive from the brittle silicon wafers that when made thin enough become flexible. Typically this type of cells are made of mono-crystalline silicon and consequently have, up-to-date, a maximum efficiency of 20%, a high value for their generation.

Nevertheless, Flexible Silicon solar cells still have a major setback, as they are less malleable than the other second generation cells and the precise value its radius of curvature - at which the cells fracture - is still unknown [27].

3.5.3 Third Generation Solar Cells

Third generation solar cells or emerging PVs endeavour to achieve first generation solar cells efficiency using second generation thin-film technique and obtain a final product with reduced costs. The objective is also the usage of non-toxic and non-limited materials.

Emerging PVs technology is at early stages and its commercialization is still weak.

As it is the most recent generation, different approaches have been proposed and pursued. The current research is in the application of multiple energy levels which can be done in three different ways: increasing the number of energy levels; multiple charge carrier pair generation with one high energy photon or unique charge carrier pair generation with multiple low energy photons and capturing carriers before thermalization [28].

Third generation photovoltaics is mostly composed by five cells: Dye-Sensitized Solar Cell (DSSC), Perovskite Solar Cell, Organic Solar Cell (OSC), Quantum Dot Solar Cell (QDSC), and Solar Paint (SP).

- Contrary to conventional cells, in a Dye-Sensitized Solar Cell (DSSC), the tasks of light absorption and charge carrier transport are assumed in two different components as an alternative to the semiconductor. The conduction is done by mesoporous oxide layer of TiO₂ deposited on a conducting oxide on a substrate and the absorption by an nanocrystalline film of charge-transfer dye. DSSC offer flexibility, lightweight, many design opportunities with its varied colours and transparency, payback time inferior to one year, efficiency up to 12% and low manufacturing costs compared to conventional PVs [29].

- Considered the solar cells with the fastest improvement to date, due to the advance in its PCE from 3.9% at 2009 to 23.3% at 2018, Perovskite Solar Cells are as well, the most efficient of the
emerging PVs, a great contrast when compared with the DSSCs, which they stem from. However, despite its high PCE, Perovskite Cells have a low impact in the commercial market, fact that comes from its severe stability issues that remain unsolved.

- Organic Solar Cells (OSC) are constituted by conductive polymers or small organic molecules. They have donor-acceptor (D-A) bulk-heterojunction structures, which currently use non-fullerene acceptors to enhance its performance in terms of PCE. Up-to-date the highest efficiency, 17%, was achieved by a tandem non-fullerene OSC based on an (A-D-A) type molecular framework. Room for improvement is seen in the low charge mobility of the organic materials which puts a restriction on the active-layer thickness and efficient light absorption [30,33].

- Quantum Dot Solar Cells (QDSC) are semiconductor nanocrystals with typical diameter variation from 3 nm to 20 nm. Their fascinating small size allow them to have astonishingly optical properties as size-tunable light emission, larger absorption coefficients, among others, as for their electrical properties QDs have high band gap and large intrinsic dipole moments [31]. In 2017 the higher efficiency know to date of the QDSC was reached - with the value of 13.4% -, by the mixing of the Perovskite and quantum dot technologies [32].

- Solar Paint (SP), also known as PV Paint, is the newest of the emerging PV technologies and the single one that is not yet considered a consumer-level product due to its still low efficiency, which fluctuates from 3 to 8%. Despite the difficulties, so far not overtaken, the idea of a coat of paint able to cover any surface, easy and cheap to install, conveys the idea of a revolution at the photovoltaic field. Up to date there are two different types of SP being researched: Solar Paint Hydrogen and Quantum Dot Solar Paint.

Developed by a team of researchers in 2017, Solar Paint Hydrogen, is based on a new compound, molybdenum-sulphide, that similarly to the silica gel can absorb the water vapour. This material also acts as a semiconductor, catalysing the reaction of the water atoms that are split into hydrogen and oxygen. Mixing it with the titanium oxide, frequently used in paints, it "leads to a a sunlight-absorbing paint that produces hydrogen fuel from solar energy and moist air" [34].

QDs are produced recurring to various methods being the most common is a colloidal synthesis. This makes them easy to handle (in a colloidal liquid form), facilitating a distribution on a substrate by spray painting, reel-to-reel printing and similar, characteristics needed by a solar paint.
State of the Art

Contents

4.1 Problem Description .................................................. 20
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4.4 Collected Data ....................................................... 30
A problem is a key component in the development. Its existence makes the human being strive to overcome the challenge and reach a much desired solution. Solutions are many times not unique and neither are the ways to approach the problem. However, there is a common factor in problem solving: investigation, being it by the analysis of similar and related works or study of variables that may affect it.

The following chapter consists in the state of the art, therefore, the problem in study will be presented as well as the variables that affect its performance together with the researched studies with significant knowledge about it.

4.1 Problem Description

As it was aforementioned, the purpose of this thesis is the study of the effect the implementation of solar photovoltaic panels in the aircraft structure will have in the autonomy of UAV time of flight. To accomplish this objective and Military Academy made available the plans of the UAV to be used, that can be observed in figure 4.1. Its measurements will be specified in the present section.

![UAV model to be used provided by CIAFA and Military Academy.](image)

The considered aerial vehicle has achieved a maximum continuous flight duration of 40 min in the electrical propulsion configuration, availing itself of 3.7 V nominal voltage Li-Po batteries, due to its good energy density, light weight and flexibility. Ten battery cells are used, in a series configuration, to feed the propulsion system and only three are appointed to power the remnant systems.

In the case study, it is of utmost importance to take into consideration the altitude at which the machine flies, thereby, taking into account some of the variables that affect the performance of the solar cells. By definition, altitude is a distance measured between a reference and an object or point. In this work, two different references are regarded: ground and sea level. The first grants that the UAV’s observation conditions are optimized when keeping a distance to it from 200 m to 800 m, preferably 400 m and the second enables the assessment of the aerodynamic and propulsion questions. According to the sea level, the maximum altitude at which the UAV flies is 2000 m.
Some other behavioral habits were also provided by the CIAFA. To summarise, this specific UAV model also has an average velocity of $100 \text{ km h}^{-1}$ and it has a range of actuation with values near 20 km over land and 5 km over sea. When climbing the aerial vehicle has an Angle of Attack (AOA) of 30° and for the cruise flight a much minor angle of 3°.

The energy steamed in the solar panels is expected to be able to enhance the aerial vehicles time of flight by its storing in the batteries, narrowing the effects of the propulsion and other systems power consumption. In order to do that, appropriate solar cells need to be chosen. However, before any considerations can be made, it is of utmost importance to know the UAV's available area for implementation. Its calculation was made and explained in the Appendix A, where the values of $280502 \text{ mm}^2$ and $55300 \text{ mm}^2$ were obtained from one wing and for one boom, respectively, prefacing a total of 0.670 604 m² for the object of this thesis’ area.

In order to adapt the solar cells to the accessible area, some parameters need to be taken into consideration, such as the flexibility - so that a good fit in the airplane structure can be made -, and the weight, guaranteeing that the vehicle's dynamic of flight will not be prejudiced.

### 4.2 Photovoltaic Technology Selection

When choosing a solar technology it is of utmost importance to guarantee its compatibility with the surface which will support the cells. As it was previously referred, the object of thesis is extremely sensitive to additional weight, and consequently, based on the prior description of the photovoltaic generations, the wafer based solar cells were the first to be excluded due to its hardness and high weight. With only the second and third generations remaining to consider, and taking into account that both technologies are light weight and adaptable to surfaces (flexible), the efficiency was the chosen criterion, and accordingly, the organic solar cells were eliminated.

Presented in chapter 3, all the five thin-film photovoltaic cells were regarded as fine candidates and it is important to refer that any of them could have been used in this project. However, Hydrogenated Amorphous Silicon and CZTS, being the ones with the lower efficiency of the group (under 20%) were also set aside. By opposition, CIGS and CdTe, presenting the higher PCE of the generation, have, nonetheless a major setback: the presence of toxic materials in its composition which need to be treated carefully, as it is important to ensure the recycling. As a result of its high efficiency and accessible non-toxic material, Flexible Thin Crystalline Silicon solar cells, were chosen as the preferred to coat the UAV.

Typically this type of cells have a thickness between $20 \mu \text{m}$ and $50 \mu \text{m}$, length from 50 mm to 100 mm, width with range from 0.5 mm to 1.5 mm and are most commonly made of mono-crystalline silicon [27]. While they are thin-film solar cells, Flexible Silicon, are not as malleable as the rest of this generation.
cells, due to their based material (silicon) brittle nature at low temperatures - values above 500 °C would be needed before a transition to ductile could occur.

The simple way to explain is through the stress-strain graphic present at figure 4.2 where two curves can be observed, the red corresponding to a brittle material and the green to a ductile one. It can be seen on both curves a yield point, when the material reaches the limit of the elastic behaviour and plastic deformation begins, being it extensive for the green curve and narrow for the red. The area under the curve corresponds to the energy absorption, its observation permits the conclusion that brittle materials absorb small amounts of energy before fracture, the opposite happens to ductile materials.

![Stress-strain curves of brittle (red) and ductile (green) materials. Adapted from [35].](image)

The consequences of this property will fall on the radius of curvature that the solar cells will be able to withstand before fracture, as unlike the other thin-film solar cells, they will only support a modicum of plastic deformation, negating its ability to bend full 360°. The theoretical radius of curvature, \( r \) can be calculated with resort to equation 4.1. It is proportional to the thickness of the silicon, \( t_{\text{Si}} \), to its Young’s modulus or modulus of elasticity, \( E \), and inversely proportional to its tensile yield strength, \( \sigma \).

For the material \( E \) and \( \sigma \) values of approximately 168 GPa and 0.7 GPa are assumed, respectively. The thickness, as it was aforementioned, it can vary from 20 \( \mu \)m to 50 \( \mu \)m, in this case 50 \( \mu \)m will be used, to guarantee the maximum curvature.

\[
r = \frac{E \times t_{\text{Si}}}{\sigma}
\]  

Although the theoretical value of the Flexible Silicon solar cell’s radius of curvature can be calculated, studies which have done the tests of bending slices of thin silicon reached the conclusion that its practical value is significantly higher than the analytical. Blakers and Armour, in their study on Flexible Silicon...
solar cells came to the conclusion that a cell with thickness of 50 \( \mu \text{m} \) has a breaking radius from 8 mm to 21 mm. In order to have a better understanding of the flexibility of the cells this values were converted to degrees - based on a radius of 25 mm - , achieving values from 19° to 48°, approximately. Bearing in mind the surfaces of the UAV that need to be covered, the curvature that the cells can endure is more than enough for them to be applied without fracture, making its choice valid in this question.

4.3 Solar Cell Performance Fluctuation

The Laws of Nature rule the world regardless of Man’s attempt to counteract them. By being built upon a renewable energy, solar PV technologies are even more dependant on Nature’s phenomena and its consequences. With the to be used solar cell chosen, the emphasis will be on the variables that can make its performance fluctuate, either in a favorable or detrimental way.

4.3.1 Influence of the Wind

In its definition, wind is the movement of gases that by a difference in the atmospheric pressure are forced to move from the higher to the lower pressure areas. Variations in the velocity of movement are caused by the augment or diminish of pressure in between the starting and stopping areas. The relation is one of direct proportionality, where a higher difference causes an increase in the velocity and a smaller difference causes a decrease in velocity.

In order to recreate a wind flow the most similar possible to reality, it is considered a turbulent wind flow. Turbulent flow is characterized by its irregular and chaotic fluctuations in the particles’ movement, with rapid variations of pressure and velocity. At the polar opposite stands the laminar flow, which has smooth movements, horizontal layered directions and constant velocity through time. It is possible to achieve a transition between flows if a considerable augment of the laminar flow velocity occurs.

For a chaotic flow the velocity is not constant, therefore, is defined by a time average component \( \bar{u} \) - the only needed if the flow was steady and laminar -, and a turbulent fluctuating time dependant component \( u' \). A bigger \( u' \) implies a more turbulent flow. The velocity through time is then expressed by equation 4.2:

\[
\begin{align*}
  \mathbf{u}(t) &= \bar{\mathbf{u}} + u'(t) \\
  (4.2)
\end{align*}
\]

Thinking of a flow in a pipe, the flow average velocity profile increases drastically when slightly away from the wall and after remains approximately constant due to the mixing between different layers of flow, introduced by the turbulence. A no-slip condition exists right at the pipe wall, ensuring that the flow velocity there is always zero. This condition also makes high shear stresses near the wall, resulting in
the creation of a very thin boundary layer. The boundary or turbulent boundary layer has two different layers: the buffer layer and the laminar or viscous sub-layer. At the closer to the wall layer (viscous sub-layer) the viscous forces - frictional forces due to fluid viscosity -, dominate and the flow is laminar. The above layer is the buffer, where both viscous and turbulent effects are significant, resulting in a mix of both flows. The upper limit of this layer is the turbulent boundary, that denotes the end of both the buffer and the turbulent layers. Above it, the turbulent effects dominate and by consequence the flow is turbulent.

The turbulent flow has whirls regions called eddies. They are part of an energy cascade where large eddies - whose have high energy -, feed the creation of small eddies that will hereafter dissipate into heat due to viscosity. Lewis Fry Richardson said “big whirls have little whirls that feed on their velocity and little whirls have lesser whirls and so on to viscosity”.

Navier-Stokes are a set of differential equations which express the motions of fluids by describing how its characterization parameters - like the density, temperature, pressure and velocity - are related. They have a wide range of practical uses, for example the modeling water currents, the weather, air flow, which all insert itselfs on the modeling flow field. The set of equations\[4.3\] counts with the fluid density \( \rho \), the fluid velocity \( \mathbf{u} \), the fluid pressure \( p \) and the fluid dynamic viscosity \( \mu \). Studies of the turbulent flow are based on the use of computational power to try and solve the Navier-Stokes equations. These assessment techniques will be addressed on the following chapter.

\[
\begin{aligned}
\rho \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) &= -\nabla p + \nabla \cdot \left[ \mu \left( \nabla \mathbf{u} + (\nabla \mathbf{u})^T - \frac{2}{3} (\nabla \cdot \mathbf{u}) I \right) \right] + \mathbf{F} \\
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) &= 0 \\
\rho &= \rho(p,T)
\end{aligned}
\]

The wind velocity decreases with the proximity to the ground due to the effect of the ground roughness on the wind’s kinetic energy [36]. A rise of the height causes an increase in the velocity of wind until a certain value of the first is reached. This value is the superior limit of the Atmospheric Boundary Layer (ABL) - with the inferior being the ground -, which is the layer “immediately affected by dynamic, thermal, aerosol, greenhouse-gas and other impacts from the Earth’s surface”, guaranteeing the influence of the fluid viscosity or friction on the airflow. The ABL is the lowest layer of the Troposphere - which extends itself for roughly 10 km -, and its height or thickness varies, from a few dozen meters to some kilometers (normally not more than 2 km), depending on the surface roughness [37].

For the variation of wind speed with height, inside the boundary layer, the logarithmic profile law can be used, giving the the horizontal wind speed for the desired height. Equation\[4.4\] describes the logarithmic profile law, where \( v_h \) is the velocity at the desired height \( Z_h \), \( v_{an} \) is the velocity at the anemometer height \( Z_{an} \) and the term \( Z_0 \), the surface roughness length, also comes into view. This parameter is expressed in meters and characterizes the hardness and stability of the surrounding land. The values it can take are presented on the table\[4.1\]
\[ v_h = v_{an} \times \left| \frac{\ln \left( \frac{Z_h}{z_0} \right)}{\ln \left( \frac{Z_{an}}{z_0} \right)} \right| \] (4.4)

The presence of the modulus wasn’t always needed whereas when this equation was made, the wind forecast was based on the anemometer height, 10 m. Nowadays, despite the anemometer still being used in weather stations, the measurement of the wind made available is based on the medium height of the human face, 1.5 m, enabling the possibility of a negative denominator if the terrain hardness is higher than the anemometer height.

Table 4.1: Values of \( z_0 \) according to terrain hardness. Adapted from [39].

<table>
<thead>
<tr>
<th>Terrain Hardness</th>
<th>( z_0 ) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very smooth, ice or mud</td>
<td>0.00001</td>
</tr>
<tr>
<td>Calm open sea</td>
<td>0.0002</td>
</tr>
<tr>
<td>Blown sea</td>
<td>0.005</td>
</tr>
<tr>
<td>Snow surface</td>
<td>0.003</td>
</tr>
<tr>
<td>Lawn grass</td>
<td>0.008</td>
</tr>
<tr>
<td>Rough pasture</td>
<td>0.010</td>
</tr>
<tr>
<td>Fallow field</td>
<td>0.03</td>
</tr>
<tr>
<td>Crops</td>
<td>0.05</td>
</tr>
<tr>
<td>Few trees</td>
<td>0.10</td>
</tr>
<tr>
<td>Many trees, few buildings</td>
<td>0.25</td>
</tr>
<tr>
<td>Forest and woodlands</td>
<td>0.5</td>
</tr>
<tr>
<td>Suburbs</td>
<td>1.5</td>
</tr>
<tr>
<td>City center, tall buildings</td>
<td>3.0</td>
</tr>
</tbody>
</table>

When plotting the wind velocity from ground to the boundary level, it is expected that it exhibits an exponential shape which will reach its maximum at the upper height limit of the ABL. It was above-mentioned, but nevertheless important to reaffirm, that the atmospheric boundary layer limit can derive from a few dozen meters to some kilometers. The calculations of this frontier height are not at all simple and thanks to [CIAFA] who provided its value for the aerial vehicle area of actuation, were not made in this study. 2000 m will then be considered as the atmospheric boundary layer cap.

The wind can influence the solar panels in two different ways. One of them is the accumulation of airborne particles (dust) by action of wind. These particles can reduce the cells’ efficiency by effect of shading and insert themselves inside electronic devices causing a malfunction. For this particular case, as the [UAV] will be most of the time at considerable heights and in movement, the settle of dust in the surface of the cells will be a much harder task. However, not discarding its occurrence, even with the low probabilities, as the vehicle will return for the base within short periods of time, the dust can be eliminated, completely removing the hypothesis of its accumulation.
4.3.2 Influence of the Cell Temperature

It is a known fact that the PV conversion is dependant on the solar irradiation. Nevertheless, the solar cell surface's temperature is also an important parameter - due to the semiconductor's sensitiveness to heat -, whereas its rise will significantly decrease the cell's output power. As such, the other way wind can influence the solar panels is by decreasing its surface temperature.

A study made by John K. Kaldellis, Marina Kapsali and Kosmas A. Kavadias analyzed the effect the velocity of wind can have in the cell's temperature. They concluded that with the increase of the wind's velocity the difference of temperature between the ambient and the cell was diminished. Their interpretation was based in collected data plotted in a graph, that can be seen in figure 4.3. $T_c$ is the cell temperature and $T_a$ is the ambient temperature.

![Figure 4.3: Impact of wind speed on temperature difference between PV modules and the environment taken from [40].](image)

By evaluation of figure 4.3 results, the wind's influence on the PV module stands out, with almost a diminish of $1^\circ$C in the difference between the ambient temperature and the cell temperature, per augment of $1\text{ m s}^{-1}$ of wind's velocity. A negative variation in the difference $T_c - T_a$ is, with the condition of $T_a$ constant, a decrease in the cell temperature and vice versa. Bearing in mind the environment the UAVs solar cells will be subjected to, it is postulated the significant influence the velocity of the wind will have on the solar cells. However, despite the incontestability of Kaldellis, Kapsali and Kavadias’ study, the photovoltaic technology is complex and therefore the variation cannot be considered equal on all solar technologies.

To find out how wind speed affects the cell temperature there must be a way to make its mea-
surement. Unfortunately, for most photovoltaic installations direct assessment of the temperature is not available, thus, theoretical models are used. In order to discern the best model to use, it was consulted a study, where eight different criterion - which all "parameterize the physical relation between cell temperature, incoming irradiance and relevant meteorological parameters" -, are tested. Polycrystalline silicon, microcrystalline silicon, amorphous silicon, monocrystalline silicon and cadmium telluride solar panels were used, with a 30° tilt angle and an orientation of 8.5° west of south [41].

The conclusions apropos the performance of different models in estimation of the solar cell temperature used both in-situ and European Center for Medium-Range Weather Forecasts (ECMWF) measurements with fifteen minute data, hourly mean and daily mean, which were inserted in RMSE and R² calculations. By analysis of its values it can be established that the better approach for monocrystalline solar cells is the Skoplaki 2, closely followed by the Mattei 2.

Skoplaki 2 is an advanced model which derives from the Standard approach (equation 4.5) by the inclusion of wind data. In the Standard approach or NOCT-Sandard-formula, the most commonly used for cell temperature $T_c$ calculation, the wind cooling effect is not included. It is determined according to equation 4.5 and it is based on Nominal Operating Cell Temperature (NOCT) conditions, where $T_{NOCT}$ defined as the temperature reached by open circuited cells (different for each cell technology) measured with ambient temperature $T_{a,NOCT}$ of 20 °C, irradiance $I_{NOCT}$ of 800 W m$^{-2}$ and wind speed of 1 m s$^{-1}$. $T_a$ is the ambient temperature and $I$ is the in-plane irradiance.

$$T_c = T_a + \frac{I}{I_{NOCT}} \cdot (T_{NOCT} - T_{a,NOCT}) \quad (4.5)$$

Equation 4.6 describes the Skoplaki 2 model. It is composed by the Standard approach (first part of the equation) together with wind data and Standard Test Conditions (STC) resulting parameters. STC are the industry standard conditions under which solar panels are tested. There is guaranteed an irradiance of 1000 W m$^{-2}$, ambient temperature $T_{STC}$ of 25 °C and an air mass of 1.5, from which parameters like the efficiency $\eta_{STC}$ and the temperature coefficient of maximal power $\beta_{STC}$ are determined.

$$T_c = \frac{T_a + \frac{I}{I_{NOCT}} \cdot (T_{NOCT} - T_{a,NOCT}) \cdot \frac{h_{w,NOCT}}{h_{w}(v)} \cdot \left[ 1 - \frac{\eta_{STC}}{\tau \cdot \alpha} \cdot \frac{I}{I_{NOCT}} \cdot \frac{h_{w,NOCT}}{h_{w}(v)} \cdot (T_{NOCT} - T_{a,NOCT}) \right]}{1 - \frac{\beta_{STC}\eta_{STC}}{\tau \cdot \alpha}} \quad (4.6)$$

This model also considers the transmittance of the cover system $\tau$, the absorption coefficient of the cells $\alpha$ - the value for $\tau \cdot \alpha$ will be assumed as 0.9 - and the wind convection coefficient $h_w$, defined in Skoplaki 2 by the parameterization 4.7, where $v_h$ is the velocity of the wind at desired height. Lastly, $h_{w,NOCT}$ is the wind convection coefficient for wind speed under NOCT conditions, which, similarly to the last described variable relies on equation 4.7 with $v_h$ equal to 1 m s$^{-1}$.

$$h_w = 5.7 + 2.8v_h \quad (4.7)$$

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4.3.3 Influence of the Pressure

The physical force exerted on an object, with a perpendicular direction to its surface, measured per units of area, is what defines the pressure. Pressure, in Pascal, \( \text{Pa} \), is directly proportional to the exercised force and area of application. In the case study pressure is more specifically called surface pressure. It is exerted by the fluids in the aircraft structure and is simultaneously caused by the air flow stopped when in contact with the vehicle surface, the air pressure and the \text{UAV} movement.

Air pressure, also called barometric pressure, is the pressure enforced by the air weight on a point or place of the Earth's atmosphere. It is intuitive to think that a high-pressure area is associated with a large atmospheric mass above its location, on the contrary, low-pressure areas have a smaller atmospheric mass overhead its location. To summarise, whereas altitude rises the atmospheric pressure declines, being the reason for that the decrease of the overlying atmospheric mass \[42\].

A method to calculate the air pressure, \( P_{hs} \), is provided in equation \[4.8\]. It considers the pressure at sea level \( P_0 \), the desired height \( h_s \), to which it is subtracted the height at the bottom of the atmospheric layer \( h_0 \), along with its respective temperature \( T_{hs} \) and uses the following constants: universal gas constant, \( R \), with value \( 8.3143 \, \text{N m mol}^{-1} \, \text{K}^{-1} \), gravitational acceleration constant, \( g \), equal to \( 9.807 \, \text{m s}^{-2} \) and molar mass of Earth's air, \( M \) of \( 0.02896 \, \text{kg mol}^{-1} \). The formula deduction can be consulted at appendix \[3\].

\[
P_{hs} = P_0 \cdot \exp \left( -\frac{M g}{RT_{hs}} \cdot (h_s - h_0) \right) \tag{4.8}
\]

Air flow around the \text{UAV} surfaces is not laminar and by its nature is not uniform either. The component of this flow that exerts its force in a perpendicular orientation when compared with the forthcoming flow, is responsible for the lift force. This force, contrary to the weight, which points downwards, is pointing upwards, directly opposing it and therefore holding the airplane in the air. In the wings, the pressure differences generated by the flow-incident force on its surface, are particularly strong, being largely responsible for the lift force. All airplanes fly with an angle of attack (angle at which the relative wind meets the chord) bigger than zero to guarantee the existence of a lift force.

Although some components of the wind flow can have a positive effect on the \text{UAV} flight, the majority of the others will only create pressure on the surface of the airplane. The magnitude of the incident pressure will vary with the force applied by the turbulent wind flow. The latter will depend on its kinetic energy, which in turn depends on the velocity. When the kinetic energy of the flow increases, so does the pressure.

For the case study the reaction of the solar cells after being subjected to pressure is an important variable. When in contact with the photovoltaic cells, pressure can cause damage, such as fissures, having the possibility of rendering the whole module useless. The pressure a cell can take before dam-
age occurs will depend on its material and shape. This influence will be latter studied with simulations, alongside the wind flow, to make sure it is possible to apply photovoltaic technology on the UAV without the possibility of breaking.

### 4.3.4 Influence of the Irradiance

Solar irradiance or simply irradiance is the radiant energy the sun produces, changing on Earth surface over the year analogous to the planet’s rotation, becoming brighter or dimmer according to the solar distance to a specific point. Irradiance is a fundamental aspect in the maximization of the solar panel performance through its direct proportionality in the output energy the cells produce. It is normally accounted as Global Horizontal Irradiance (GHI), which is the total radiation received on an horizontal plane on Earth, composed by the sum of direct irradiance - radiation received by a surface perpendicular to the solar rays - and diffuse irradiance - radiation that has been scattered by atmosphere particles, but that nonetheless reach the surface in account.

GHI is most frequently associated with the printed maps that relay the irradiance values for countries and zones, distinguishing between its range with colours. By consequence, the concept of GHI seems to almost discard the variation of the received radiation with height, implying a constant nature. Nonetheless, this idea is misleading, as the GHI can be calculated or measured for any horizontal plane on Earth, undeterred by the desired height.

Common solar installations are only a few dozen meter high, the grand majority not passing the 100 m limit, as such the height is not considered a extreme factor in its parameter evaluation. For the described cases, GHI typical measures (ground level) will produce a good estimate for the panel output, however in this study the solar cells will be subjected to substantial heights, being the maximum 2 km.

Irradiance suffers an augment as altitude increases. The influencing factors for that variation are first and foremost optical path and ground albedo. It is almost instinctive to affirm that when reducing the geometrical path length from origin to destination an enlargement of the "receiving signal" will occur, in essence, the optical path can be viewed as a function of the altitude, for its diminish will imply a consequent decrease on the attenuation of the radiation by the atmosphere. Likewise, clouds, aerosols and water vapors - predominantly located in the lower atmosphere - also play a part in the radiation's weakening. Lastly, the ground albedo or reflection coefficient will have an impact on irradiance diffuse component (proportional to the albedo) which will be higher as proximity to ground increases, thereupon reflecting negatively on GHI [43].

There are many researches concerning the best approach to determine the variation of the received GHI with altitude. For this study, while the fluctuation of the parameter was theoretically investigated and its importance explained and recognised, none of the existing models is intended to be used for its values, for the desired height, will be considered at subsequent simulations.
4.4 Collected Data

Before any implementation can be made, data concerning variables such as wind speed, location and irradiance, that could affect the vehicle’s performance, needs to be considered and researched. As it was above-mentioned, the case study is based in a UAV that has a range of $20\, \text{km}$ over land and $5\, \text{km}$ over sea. Usually the aerial vehicle in question departs from the CIAFA which is located at Pêro Pinheiro, Lisbon district, reason why in this thesis it will be considered, for simplification, the starting point.

The UAV’s radius of action is presented at figure 4.4 delimited by the blue geometric form. It is centered at Pêro Pinheiro and stretches itself for the already announced $20\, \text{km}$ over land, with the reduced $5\, \text{km}$ when water is involved, motive for the existence of an imperfect circle (straight cut) near the ocean.

![Figure 4.4: UAV’s radius of actuation, delimited by the blue geometric form (made using [45]).](image)

Worldwide distribution of solar irradiance is mainly defined by Earth’s spherical shape, leading to a more concentrated incoming solar irradiance near Equator zones, as a smaller area is covered, which results in a higher irradiance per unit of area. The opposite occurs as latitude augments, due to the coverage of a larger region [44].

Regarding figure 4.5 it presents the average yearly and daily GHI since 1994 to 2018. Portugal is considered a medium country in terms of received solar irradiance by virtue of its location, making it a good country for photovoltaic installations. Despite the fact that this GHI values are not going to be used in this study, for the previously stated reasons, they are important in order to understand if a variation of the received irradiance inside the UAV actuation area exists. When comparing figures 4.4 and 4.5 it can be concluded that the south and east zones of Lisbon and radius have slightly superior values of GHI when comparing to the rest.
In figure 4.6 the wind velocity at Lisbon district, for each of the months of 2019 can be observed. It was considered important to present the average velocities, 4.6(a), that have values comprised between 3.22 m s$^{-1}$ and 5.14 m s$^{-1}$, as well as the maximum velocities, 4.6(b), that vary from 15.94 m s$^{-1}$ to 24.17 m s$^{-1}$. These values will be subsequently used in the simulations.

(a) Average velocity. 
(b) Maximum velocity.

Figure 4.6: Velocity of wind in Lisbon district 2019 (based on [47]).
Parameter Influence on the Vehicle Structure

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With the core concepts heretofore theoretically approached or introduced, the focal point of this chapter will be the concretion of simulations, using COMSOL Multiphysics as software, in which the mentioned parameters influence on the UAV structure is evaluated. The simulations construction, as well as the results, will be addressed.

5.1 UAV Construction

With the object of this thesis being an UAV where the solar cells are proposed to be installed, there is a need to simulate the in study variables, like the wind flow and the pressure, around its structure. Furthermore, bearing that in mind, a 3D model of the to be used aerial vehicle was constructed, with resource to COMSOL Multiphysics Geometry. The measures for each component were provided by CIAFA along with the technical drawing present in appendix A.

To simplify the work, the UAV was divided in parts, grouping the geometrically similar ones, with the idea to join component to component until the airplane was completely formed. The wings were chosen as the base to start drawing. They were made first in a 2D yz plane, with parametric curves, and after extruded (in the x axis) to the desired width of 2.508 m. Figure 5.1 form is the result of this operations, where it is important to mention, the ailerons are not in due to the little utility they bring to the simulation. All of the figures generated with COMSOL Multiphysics will contain an axis framework on the left cornered to ease the tridimensional visualization.

![Figure 5.1: Wings drawn prototype using COMSOL Multiphysics.](image)

Next, the booms and the tail were drawn, in 3D from the start, as they are made of simple geometries like prisms and straight-lined polygons. The tail is composed by the rudders, elevator, vertical and horizontal stabilizers. All these, together with the wings, can be seen in figure 5.2.

For the "body" or fuselage, a separate geometry component was created guaranteeing that its overlap with the wings would not interfere with the drawing. Observing figure 5.3 the nose and the fuselage can be seen. A further division in upper, middle and lower fuselage was needed to represent it, by cause of the structure complexity. The upper and lower segments were made with resource to 3D ellipsoids, cut by the middle on both the yz and xy planes. A composition of ellipsoids were also used to form the
middle segment - which is not hollow in the intern part -, all cut on the yz plane. An ellipsoid was also used to form the nose.

Joining all the components presented so far, resulted in the final aerial vehicle of figure 5.4 where a front (figure 5.4(a)) and lateral (figure 5.4(b)) can be seen. It is important to refer that the line and surface blurring, extant in all geometry related COMSOL Multiphysics produced images, is pinned on the software image rendering and not on a drawing defect.

Before any simulations can be ran, it is necessary to attribute a material to the geometric entity. The physical unmanned vehicle is made of a composite material which includes fiber glass, carbon fiber and epoxy resin. Its properties make it resistant and light in order to ensure the structure withstands the
mechanical stresses that it is subjected to, and at the same time that its weight does not over burden the motor subsequently increasing the energy consumption. Ideally, the material chosen for the simulation should be the same the physical [UAV] is made of, however, the most similar one is a composite with only fiber glass and epoxy resin, forgoing some of the strength the carbon fiber endows the composite with.

5.2 Wind Tunnel Simulation

Wind flow around the [UAV] structure will be studied with resource to the COMSOL Multiphysics Turbulent Flow module. This module aims to solve the aforementioned Navier-Stokes equations by modeling the fluid domain around the airflow, as a mesh of discrete elements. Finer the mesh, more precise the results are, however, it is always a trade, as thinner mesh elements imply more computation time.

The equations will be evaluated with resource to a computational assessment technique. Up-to-date there are three different techniques: Direct Numerical Simulation (DNS), which solves all the eddies, from the largest to the smallest, Large Eddy Simulation (LES), where only the large scale eddies are resolved and Reynolds-Averaged Navier-Stokes (RANS), a completely different time averaged method which does not resolve eddies explicitly, choosing to instead model its effect using the concept of turbulent viscosity. RANS is not an explicit method and therefore is less computationally expensive, being that the primary reason for its use in this work.

After choosing the assessment technique or turbulence model type, a turbulence model needs to be chosen accordingly. For the RANS, COMSOL Multiphysics makes available nine different turbulence models (whose can be consulted at the software library), however, for the case study the k-\( \epsilon \) turbulence model - where k refers to turbulent kinetic energy and \( \epsilon \) the rate of dissipation on turbulent kinetic energy - is selected. From within the reasons behind its election, its good performance for complex geometries, its stability and the possibility to use wall functions stood out. Wall functions are adopted to resolve the thin boundary layer near the wall, preventing the use of a very fine mesh. Essentially they provide an offset so that the mesh does not need to go near the wall, moreover, being the solution there straightforward, a relationship is used to characterize the flow.

An incompressible flow approximation is used, assuming the fluid’s density as constant, implying that the diverge of the fluid velocity is zero, as such the continuity equation yields: \( \nabla \cdot \mathbf{u} = 0 \). By consequence the term \( -\frac{2}{3} \left( \nabla \cdot \mathbf{u} \right) \mathbf{l} \) in the first equation of the Navier-Stokes (4.3) can be removed. A stationary analysis is also considered. The RANS equations deduction - starting from the Navier-Stokes -, can be consulted in appendix C.

The simulation’s input geometry is a wind tunnel with dimensions of 3.5 m width, 5.5 m depth and 22.5 m height with the previously designed [UAV] inside, as illustrated on figure 5.5. Smaller the dimensions, lighter the computation would be, nevertheless, they can not be reduced too much, with risk of
affecting the results, on this wise, before the presented dimensions were dictated as final, some simu-
lations were ran to ensure the proximity of the walls would not prejudice the flow complexity. For the
height, the ideal would be a wind tunnel with 2000 m, so that the unmanned vehicle could be shifted to
the desired altitude to simulate. However, a geometry that substantial, mainly in comparison with the
vehicle’s dimensions, would mean an excessively above normal computational power. Instead, variables
like the ambient pressure, temperature and wind velocity at the open boundary are used as an input to
replicate the desired altitude conditions.

Before declaring the typology as the final geometrical structure, a "test-run" simulation was in order.
It was concluded that with the current down wing curvature, around 2000 iterations would be needed to
reach a conclusion, what would take around ten days. To simplify the problem, a straight-line was used
instead. It is a valid topology to take conclusions in this work, mostly due to the lack of the influence the
down wing has on the solar cells - which will be inserted on the top wing and booms.

![Wind Tunnel simulated structure.](image)

It was expected that with the Computational Fluid Dynamics study the interactions between the fluid
and the to be included solar cells could be accounted for. It was on the best interest to both maximize and
minimize, on separate solutions, this interactions, so that the range of influence is known. To accomplish
this, the values of the input variables were varied accordingly to the desired.

First thing to contemplate is the altitude in question, only after that the other variables can be de-
termined. Concerning the wind velocity inserted at the open boundary (wind tunnel top), its value was
calculated using the previously exposed logarithmic profile law (equation 4.4). Relating the radius of
actuation with table 4.1 values, a surface roughness length $z_0$ of 3.0 m was used. From the gathered
wind velocity, only the maximum ($5.14 \, \text{m s}^{-1}$) and the minimum ($3.22 \, \text{m s}^{-1}$) average values were used.

Temperature was the next input variable to resolve. On that account, the average higher and lower
values at Lisbon district were researched, reaching values of 29 °C and 8 °C, respectively. For its vari-
ation with height a drop of 2 °C per 300 m, relatively to the ambient temperature at ground-level, will be
considered.
On the part of the reference air pressure, the previously exposed equation 4.8 is the base for its calculation. While most of its parameters are constants (whose values were already exposed), the temperature $T_h$ and desired height $h_s$ will vary according to the simulated conditions. For the remaining parameter, the height at the bottom of the atmospheric layer $h_0$, it was defined as $0 \text{ m}$. The change in the ground altitude at the radius of actuation is not constant but is never significantly higher, relatively to the considered, meaning that, per se it will not interfere drastically with the results.

In total, four different flight altitudes were simulated, being them the minimum altitude, $200 \text{ m}$, the preferential altitude, $400 \text{ m}$, the maximum altitude with reference to ground, $800 \text{ m}$, and the maximum altitude according to sea level, $2000 \text{ m}$. For each of them, the maximum $(5.14 \text{ m s}^{-1})$ and the minimum $(3.22 \text{ m s}^{-1})$ wind average velocities at Lisbon district, combined with the $30^\circ$ AOA's for the climbing, and $3^\circ$, for the cruise flight, were summed up to a total of sixteen simulations. This number was predetermined, therefore, with the results’ analysis, some of the simulations were considered useless to the conclusions, hence, never made. As the number of simulations was high, only the most significant will be here presented. Each one of them has two studies: the wind flow at the tunnel and the pressure on the surface of the unmanned vehicle.

Starting with the highest altitude - $2000 \text{ m}$ at [UAV] level and $2010 \text{ m}$ at the top -, the maximum values of temperature ($29 ^\circ \text{ C}$ at ground level) and average wind speed ($5.14 \text{ m s}^{-1}$ at ground level), the values of $48.25 \text{ m s}^{-1}$, $288.82 \text{ K}$ ($15.67 ^\circ \text{ C}$) and $79981.01 \text{ Pa}$ were calculated for the wind speed at the top boundary, reference temperature and pressure, respectively.

![Figure 5.6: Maximum wind flow in m s$^{-1}$ at 2000 m of altitude and 30$^\circ$ AOA](image)

On figure 5.6 the resulting wind flow is illustrated, being characterized by velocity magnitude, orientation and direction. The velocity magnitude’s values are differentiated by colors whose legend can be seen at the right border. As it was expected, due to the way the velocity varies with height, the maximum
is located at the top boundary, with equal value to the inserted, and its value decreases with altitude, reaching a minimum value between 40 m \(s^{-1}\) and 35 m \(s^{-1}\). Near the [UAV] a sudden drop on the velocity occurs on the account of the "shielding" the vehicle structure makes to the area immediately near it. Wind flow orientation and direction are represented by the black arrow lines at the outer boundaries of the tunnel. Its length is proportional to the magnitude. While the arrows might give the impression the flow behaves itself at a steady laminar fashion, that is not the case.

To better evaluate the flow near the [UAV] figure [5.7] is provided. With resource to it, it can clearly be verified the previously referred drop right below and in the surroundings of the structure. Furthermore, a difference in the flow velocity magnitude "passing through" the different aerial vehicle's parts is also seen, denoting that they are not all affected equally. The lowest velocity is clearly behind the structure, justified by the "shelter", the most robust part of the vehicle (fuselage plus nose) creates against the flow passage. Thinking about the aerial vehicle motion when climbing, and crossing it with the presented information, it is expected the nose, the lower fuselage - due to the path the flow takes when confronted with the nose - and the wing's leading edge to be the surfaces that "suffer" the most, sustaining the wind flow. However, it is important to refer that this study is two dimensional, as such, the flow that focuses on some surfaces, like the wings, cannot be seen in detail. Nevertheless, it can still be noticed the lower velocity in the upper wings contrasting, with a velocity higher by almost 25 m \(s^{-1}\) at the bottom wing.

![Figure 5.7: UAV focused view of maximum wind flow magnitude in m s\(^{-1}\) at 2000 m of altitude and 30°AOA](image)

Both bottom and lateral views were chosen - illustrated on figures [5.8] and [5.9] respectively - to assess the pressure study, which, like the wind flow one is differentiated by colors whose legend is present at the right border. It is important to reinforce that a reference pressure for the air surrounding the vehicle is provided, therefore, all the displayed values are relative to it, being the reference treated as a "zero" for the referential.

Being directly related with the air flow, it was expected a high pressure on the nose, lower fuselage, and down wing which is verified by the figures, where the highest pressure is located on the nose.
Thinking about the UAV motion when climbing, the nose directly faces the flow, which will escape both by the top and bottom fuselage. The part that escapes to the top will mostly ascend and combine with the flow that is essentially not influenced by the airplane, thus never exerting its force on the upper fuselage. On the contrary, the flow that escapes downwards exerts pressure in the lower part of the vehicle - by trying to rise -, together with the flow that directly hits it, due to its frontal position in the movement.

![Figure 5.8: Bottom UAV focused view of maximum pressure in Pa at 2000 m of altitude and 30° AOA.](image1)

![Figure 5.9: Lateral and top UAV focused view of maximum pressure in Pa at 2000 m of altitude and 30° AOA.](image2)

Most like the nose, the airfoil lower part takes directly the flow. To simplify the analysis, figure 5.10 was generated, being an adaptation of the previous figure 5.8, with the inclusion of arrows describing the flow motion for a two dimensional xz plane, a little forward from leading edge coordinates.

When observing the previous pressure and velocity illustrations, an undeniable contrast both in the pressure and surrounding velocity in between the upper and lower wing, is seen. This difference is highly
responsible for the lift force. Focusing on the following figure air flow representation, it can be seen that when hitting the down wing, the air is confronted with the wing inclined path that will push the air below it downwards. In turn, it will apply a high force on the wing surface to follow the forced path. Its pressure on the wing will reduce as the distance to the attack border increases, as more of the air will flow upwards, attracted by the low pressure area created by the higher wind speed above the vehicle. For the air that initially flows up, it will be sucked into the higher velocity-lower pressure area above, together with the air product of the down flow.

![Figure 5.10: Maximum pressure and directional wind flow at 2000 m of altitude and 30° AOA](image)

For a different perspective, cruise flight will be considered, with a 3° angle of attack, maintaining all the other conditions - pressure, temperature, altitude and wind speed. On figures 5.11 and 5.12, the wind flow magnitude, orientation and direction are shown, with a total view of the wind tunnel and a UAV.

![Figure 5.11: Maximum wind flow in m s^{-1} at 2000 m of altitude and 3° AOA](image)
focused view, respectively. Comparing with the simulations for the climbing, a clear difference is seen both at the velocity drop and the flow orientation and direction, in the vehicle surrounding space. While for the previous simulations the wind flow magnitude had considerable variations near the unmanned vehicle - from to nearly $35 \text{ m s}^{-1}$ to $5 \text{ m s}^{-1}$, the current one has more attenuated ones - from $40 \text{ m s}^{-1}$ to $30 \text{ m s}^{-1}$. With the only changed variable being the angle, it is clear that the velocities own their values to the lack of "shielding" the UAV provides.

![Image](image1.png)

Figure 5.12: UAV focused view of maximum wind flow magnitude in m s$^{-1}$ at 2000 m of altitude and 3° AOA.

Again, a bottom and lateral views were used to evaluate the pressure in the unmanned vehicle structure, as illustrated in figures 5.13 and 5.14 respectively. Comparing with the previous pressure values, the differences begin to show at the maximum and minimum values, which augmented, in modulus, about 100 Pa. With the drastic change in the wind flow magnitude around the vehicle, consequent alterations had to occur in the surface pressure distribution. Not minding the angle adjustment, a high pressure for the nose can be seen, as the surface will always face the flow "head on".

![Image](image2.png)

Figure 5.13: Bottom UAV focused view of maximum pressure in Pa at 2000 m of altitude and 3° AOA.
Figure 5.14: Lateral and top [UAV] focused view of maximum pressure in Pa at 2000 m of altitude and 3° AOA.

To better evaluate the flow at the wings, figure 5.15 was provided, where, the pressure is shown together with the flow motion describing arrows, with thickness proportional to flow magnitude. To apply these arrows an xz plane at leading edge coordinates was used. Identical to the nose, the leading edge directly faces the flow, suffering a high pressure for this reason. This edge will provoke a separation, as after impact, the air will both flow up and down the wing, not on equal measures. The air that flows down will experience the same as previously described with a 30° angle, with the difference being the lesser inclination of the wing, that consequently will result in a minor force exerted by the air in the surface as it will be able to escape and ascend easily to the low pressure area.

Figure 5.15: Maximum pressure and directional wind flow at 2000 m of altitude and 3° AOA.

From the presented results some general conclusions can be taken. It can be said that the wind may affect the vehicle surface directly, when hitting the [UAV] or indirectly, by the influence of the structure surrounding velocity. When in direct contact with the surface, a higher wind flow magnitude will induce a greater pressure in it. For the surrounding flow, that does not come into contact with the aerial vehicle,
a higher velocity of the fluid means a lower pressure (by Bernoulli’s principle) and vice-versa, thus, affecting the air flow, which tends to be attracted to lower pressure areas.

Comparing the information from the simulations the importance of the angle of attack is underlined. To guarantee the existence of the lift force - that holds the vehicle in the air -, the angle of attack needs to be greater than zero, so that when confronted with the down wing surface, its bent path pushes the air downwards, which in turn will create the pressure responsible for the lift. The pressure is proportional to the angle of attack.

For the vehicle to decrease altitude or land, a reduction of the lift force is required. These motions are made by decreasing the angle of attack and deflecting the elevators down. Nevertheless the pressure created at the top of the wings will not be much higher than the simulated, as summed to the weight it would highly unbalance the vehicle, being this the reason these motions were not viewed important for the case study, thus never considered.

As aforementioned, the purpose of these simulations consists in the evaluation of the influence of the wind flow and pressure on the structure. Despite the object in use being the vehicle, the utmost goal is the estimation of the effect the resulting pressure will have on the panels - if they will or not break -, as it is unequivocal the constituting material is prepared to handle the resulting pressures, being built with that in mind.

At chapter 4 the upper limit of force the to be used flexible silicon cells can take without permanent damage (tensile yield strength) was exposed - when calculation the radius of curvature -, with a value of 0.7 GPa. Comparing the previous results for the pressure concentrated on the wings and booms, the maximums are attained at 30° and 3° AOA, respectively. For the wings, as it can be seen in figure 5.9, two different pressure values cover the wing surface, being the higher at the rear with value 79 750.6 Pa. Figure 5.14, booms, count with an almost constant value of pressure on its extensions, that slightly augments at the end near the tail, where a value of 80 024.05 Pa is displayed. Since none of these values are close to limit, it can be concluded that the wind flow and its ensuing pressure do not pose a threat to the solar cells integrity, thus validating the possibility for its implementation on the UAV.

Initially, sixteen simulations were proposed in order to evaluate all described combinations, however, only two, for the highest altitude and wind were used here to attain a conclusion. When performing the simulations, the start altitude was 200 m, where the pressure proved to be lower than the cells tensile yield strength, therefore, the altitudes of 400 m and 800 m were considered, one at each time, being the results the same. From that the higher altitude the vehicle is prepared to fly was considered, generating the already seen and commented results. The posed simulations provoked the maximum pressure for the respective angles of attack, and the need for additional lower altitude ones - between the 800 m and 2000 m -, would only arise in case the pressure in the wings and booms proved to be too much for the chosen cells to handle.
6 Photovoltaic Modules

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This work's intended climax consists in drawing a conclusion apropos the effect the inclusion of photovoltaic solar panels will have in the autonomy of UAVs time of flight. For that purpose, variables that can influence the panels physical integrity were described and evaluated by means of computational simulation. To culminate, the already addressed parameters that impact microscopically on the cell operation - here augmented by the abnormal distance to ground in a photovoltaic implementation -, thus on its efficiency, need to be weighed, being that the focus of this chapter.

6.1 Application Description

In order to appraise the to be included panels operation, considering the theoretically studied parameters, an application made by COMSOL Multiphysics, that illustrates the operation at an user-specified location of a Si solar cell, will be used. It is highly dependant on user specified parameters, such as the altitude, location and cell's attributes, to characterize the cell performance, making it a good fitting to the case study. To handle the different types of inputs, the application combines two COMSOL Multiphysics modules, being them Ray Optics and Semiconductor.

For the concerning Ray Optics module, the Geometrical Optics interface is used to model, for a predefined position, the received irradiance through the day, at a specific date. It is based on the ray tracing algorithm that simulates the path of light, starting from the receiver object until the source. The interest in this module is essentially the calculation of the sun position - the algorithm source -, computed from user input parameters, used to define the position in Earth - the algorithm receiver and the cell position -, such as latitude, longitude, time zone, date and time. From this study, the application will be able to define the sun's position throughout the day, expressed in azimuth $\phi$ and zenith angle $\theta$.

With that information, the determination of the air mass $AM$ coefficient - which defines the normalised direct light path length through Earth's atmosphere, taking into account its curvature -, is possible and expressed in equation 6.1 [48].

$$AM = \frac{1}{\cos \theta + 0.50572(96.07995 - \theta) - 1.6364}$$

(6.1)

The angle of incidence of the radiation on the cell's surface $\Theta_i$, calculated in the module recurring to equation 6.2, depends as well on the sun's position, in the way that the cell $n_c$ unit vector and the solar unit vector direction $n_s$ can be componentwise expressed in terms of the zenith and azimuth angles [48].

$$\Theta_i = \arccos (n_c \cdot n_s)$$

(6.2)

This module does not consider the scattering of the radiation by atmosphere particles and molecules, therefore, the direct radiation received by the solar cell from sunlight is the total and slightly augmented...
radiation. Taking into account the study conditions, where the concerning zone is inside Earth’s atmosphere, it is only necessary to use the air mass model, presented in equation 6.3 to determine the direct intensity. The model measures the intensity of the directly incident radiation $H_d$ as a function of the following parameters: altitude above sea level $h_s$, air mass $AM$ and angle of incidence $\Theta_i$ [48]. $H_0$ is the reference irradiance that will be here adapted to the average yearly value at Pêro Pinheiro, being it about 4400 W m$^{-2}$.

$$H_d = H_0 \left[ (1 - 0.14h_s)0.7^{AM^{0.68}} + 0.14h_s \right] \cos \Theta_i \tag{6.3}$$

Semiconductor’s module is used to compute the cell characteristics based on the Gauss law. To better define the conditions several interfaces are adopted, which resort to input design parameters provided by the user, naming the cell temperature, the shunt and series resistances and the azimuth and tilt angles. The used geometric model is a 1D PN junction with the anode and cathode modeled as thin ohmic contacts deposited on the emitter and base side, correspondingly. To take into account the power losses (shunt resistance, $R_{shunt}$) and the semiconductor’s plus the connecting cables resistances (series resistance, $R_{series}$), the most common equivalent circuit, illustrated on figure 6.1, is adopted [48].

![Figure 6.1: Solar cell’s equivalent circuit (taken from [48]).](image)

To model the solar cell the Semiconductor module will interact with the Ray Optics, in order to obtain the spectral irradiance, which will be subsequently used to determine the generation rate. In its turn, the generation rate depends on the absorption coefficient and the photon generation rate. Counterbalancing the complexity of the equations, some valid assumptions are made: the spectral irradiance is approximated through sun’s blackbody spectrum at temperature 5777 K and the anode is assumed as having the reflectance equal to one due to a perfect antireflecting coating [48].

With the objective of extracting the solar cell characteristics, namely the maximum power point - constituted by the voltage at maximum power $V_{mp}$ and the current at maximum power $I_{mp}$ - , the short circuit current $I_{sc}$ and the open circuit voltage $V_{oc}$, the application will generate the cell parameter corre-
spondent I-V and P-V curves. The efficiency $\eta$ will be calculated, with resource to equation 6.4 where $FF$ corresponds to the fill factor, given by the expression in equation 6.5 and $P_{in}$ is the incident power, defined by $P_{in} = H_0 A$, being $A$ the solar cell area.

$$\eta = \frac{I_{sc}V_{oc}FF}{P_{in}}$$ (6.4)

$$FF = \frac{I_{mp}V_{mp}}{I_{sc}V_{oc}}$$ (6.5)

### 6.2 Solar Cell Simulations

The solar panel performance will be considered with the resource to the COMSOL Multiphysics heretofore described application. As already mentioned, it counts with two modules to compute both the illumination and the solar cell characteristics. To adapt the application to this case study, the input variables values were shaped to the problem at hands. For a better estimation of the range of outputs the panels could produce, an attempt to achieve the maximum and minimum values for both the wings’ and booms’ cells was made.

Starting with the Sunlight Properties for the Ray Optics computation, there was a need to define both the zone coordinates, the date and the altitude. For the coordinates, taking into account the aforementioned slightly change of the GHI within it, two coordinates may be considered, one for the place pointed as Lisbon on the map, with value (38.73694,-9.14268), and the other for Pêro Pinheiro, the CIAFA location, with value (38.861077,-9.320995), corresponding to the maximum and minimum GHI, respectively. To the date, the winter and summer solstice of 2019 were used, as they contrast with the shortest and longest light hours. Finally, for the altitudes, bearing in mind the variation of the irradiation and wind velocity with it, the maximum (2000 m) and the minimum (200 m) will be taken into account.

With regard to the coordinates, before excessive simulations were made unnecessarily, two simple plots were produced of the direct irradiance in function of the elapsed hours at the altitude of 2000 m, for the date 21 June 2019. The highest direct irradiance is at 1pm for both, with a value of 1031 W m$^{-2}$ for Lisbon and a value of 1030 W m$^{-2}$ for Pêro Pinheiro, completely removing the need to examine the two coordinates, as their variation of irradiance is insignificant. Keeping that in mind, it was decided to consider only Pêro Pinheiro, as it is the starting position for the UAV’s flight.

To characterize the cell properties, the cell temperature, the shunt and series resistances and the azimuth and tilt angles were detailed. The cell temperature will be calculated with resource to equation 4.6, where the non-constant values, like $T_a$ and $h_{w,NOCT}$ will depend on the considered altitude, thus, will be further specified on the respective simulation. For the solar cell series and shunt resistances, good commercial values are 1000 $\Omega$ cm$^2$ for the first and 0.5 $\Omega$ cm$^2$, which, according to the cell area of
25 mm², will have the final values of 4000 Ω and 2 Ω.

Commonly, the azimuth is defined as the angle between the object and the meridian of the location, being for the north hemisphere referent to south and defined as positive to west. However, the program was made with the south hemisphere in mind, intrinsically making the azimuth referent to north and defined as positive to east. A detailed measurement of the cell azimuth angle is not feasible, for the [UAV] can fly in every direction, therefore, the simulations will be made with the maximum and minimum values. For the last property, particularly the tilt angle, the cruise flight angles are chosen, due to the reduced time the vehicle spends climbing. As a result, the angle of 3° is used for the wings and 90° for the booms.

The azimuth and tilt angles are the only parameters that exhibit a difference, amidst the booms’ and wings’ solar cells. For the booms there is even a further distinction in the azimuth angle between sides of the same boom, being this the reason for separate simulations for wings and booms. The maximization and minimization of these parameters is made for the wings, seeing that for its position and extension they will produce higher output energy.

Opening with the simulations for the maximum values, the date 21 June 2019 was used, corresponding to summer solstice, the day with more light hours of the year. Together with an altitude of 2000 m, these parameters allowed to generate figure 6.2 graphic, that illustrates both the azimuth - represented by the blue color -, and zenith - represented by the green color -, angles of the sun in degrees, over the course of the day.

All the following simulations trying to emulate the maximum values, are based in a cell temperature of 21.89 °C (295.04 K), obtained with $T_a = 15.67 °C$, predetermined $I = 1043 \text{ W m}^{-2}$ and wind velocity of 48.22 m s⁻¹.

![Figure 6.2: Azimuth (blue color) and zenith (green color) angles of the sun at 2019's summer solstice.](image)
Before an evaluation of the incident angle and direct irradiance can be made, it is of utmost importance to take into account the air mass. Bearing that in mind, figure 6.3 illustrates the air mass at an altitude of 2000 m for 21 June 2019. Like the sun position, the air mass only depends on the coordinates, time zone, date and altitude, however, despite its simplicity at calculation, its value interferes in the direct irradiance, together with the incidence angle. It can be stated that a lower air mass coefficient, together with a lower incidence angle imply a higher irradiance value.

Figure 6.3: Air mass at 2019’s summer solstice.

The preferred orientation for the solar panels in Portugal is facing south with a tilt near 35°. However, the UAV has an AOA of 3° which corresponds to a tilt of −3°, as such, its favored direction of flight to minimize the incident angle will be north, which equals an azimuth of 0°. These values originated figures 6.4 and 6.5, where the sun’s incident angle on the wings’ surface cell and the direct irradiance received by this respective cell, can be seen, by this order. In this case, the incident angle is at concordance with the air mass, so, as expected by the formula, a lower incidence angle originates a higher irradiance, being the ideal value for the first 0°, so that the cell would receive the maximum irradiance. Figure 6.5 achieves its peak at 13 h30 min - a value of 1043 W m\(^{-2}\), time at which the corresponding incidence angle is at its minimum (12.4°).

For every sunlight incident simulation the values are only displayed since the sun rises until the sun sets. If a value is not present for the sunlight incident angle, the direct irradiance is programmed to be assumed as zero.

The UAV in context has two booms with a right side and a left side each. To simulate this situation, different azimuth angles were used for the faces with distinct faces, always with a tilt angle of 90°. When the vehicle is flying north, each boom has a side facing east and another facing west.
To emulate the east faces, an azimuth angle of 90° is used, generating the sunlight incident angle graphic illustrated in figure 6.6 and the analogous direct irradiance in figure 6.7. By facing east with a 90° tilt, it is natural for the cell to only receive light in the morning and early afternoon hours, and even then the incident angle values will be higher when compared to the wings. In this case, the air mass is not totally concordant with the sunlight’s incident angle, meaning that for each case, the punctual dominant variable will influence more the irradiance values, as such, a lower angle of incidence does not always mean a higher irradiance value. This is precisely what occurs for the maximum irradiance value (near 800 W m$^{-2}$), that does not correspond to the lower sunlight incident angle.
A rotation of 180° from the east faces azimuth angle is used to generate the west ones, which count with an azimuth of 270°. The graphics for the sunlight incident angle and direct irradiance can be observed in figures 6.8 and 6.9 respectively. Due to its azimuth and tilt angles’ values, the west side booms only start to receive light in the afternoon, almost right when it ends for its counterparts. Here, in a more accentuated way than for the previous simulations, it can be said that the air mass is not totally concordant with the sunlight's incident angle, as at two in the afternoon, when the air mass starts to increase, the incident angle starts to decrease. However, the angle variation has a more accentuated
effect on the direct irradiance, for it increases with the angle's diminish.

![Figure 6.8: Sunlight's incident angle (°) on the west side booms' surface cell at 2019's summer solstice.](image)

![Figure 6.9: Direct Irradiance (W m⁻²) received by the cell at 2019's summer solstice, referent to the boom's west sides.](image)

The last simulations are made with the objective to produce the minimum values possible, so that a complete range of the output energy is made. For the date, the winter solstice, 22 December 2019, the shortest day of the year, was chosen, together with an altitude of 200 m. With these parameters, the sun azimuth - represented by the blue color - and zenith - represented by the green color - angles of the sun through the course of the day, are modeled, being shown in figure 6.10. Lastly, the common (to all simulations) parameter, the cell temperature, was calculated, having the value of 21.1 °C, obtained with
$T_a = 6.67 \, ^\circ C$, predetermined $I = 388 \, W \, m^{-2}$ and a wind velocity of $19.51 \, m \, s^{-1}$.

Air mass is the last general simulation and is represented in figure 6.11. Its conditions, like for the sun position, are the already mentioned altitude and date. Comparing this values with figure 6.3 ones, the difference between seasons is obvious. The reduced daily extent of the air mass will have its repercussions in the direct irradiance, being it for the wings or booms.

Figure 6.10: Azimuth (blue color) and zenith (green color) angles of the sun at 2019’s winter solstice.

Figure 6.11: Air mass at 2019’s winter solstice.

For the minimum values, it was considered an UAV flying in south direction (azimuth of $180^\circ$) with a tilt angle of $-3^\circ$. These values were behind the creation of figures 6.12 and 6.13 where the sunlight’s incident angle on the wings’ surface cell and the direct irradiance received by this respective cell, can be seen, respectively. Comparing to the wing’s last results, a clear reduction of the active hours can be
seen, both on the incident angle and direct irradiance, which will have major implications on the output energy the cell can produce.

![Figure 6.12: Sunlight incident angle (°) on the wings’ surface cell at 2019’s winter solstice.](image)

![Figure 6.13: Direct Irradiance (W m$^{-2}$) received by the cell at 2019’s winter solstice, referent to the wings.](image)

There is no need to distinguish the maximum and minimum value simulations in terms of booms’ angles. So, bearing that in mind, the east faces will still have an azimuth of 90° and the same value for the tilt angle, generating the sunlight incident angle graphic illustrated in figure [6.6] and the analogous direct irradiance in figure [6.7] Despite the direct sunlight incident angle having values since eight in the morning until early afternoon, the direct irradiance will only start to increase at nine, due to the elevated
air mass coefficient value. In the first four values or the irradiance, notwithstanding the augment of the incident angle, an increase of the direct irradiance can be seen, indicating a dominance of the air mass on the equation.

![Graph showing sunlight incident angle and direct irradiance](image)

**Figure 6.14**: Sunlight incident angle (°) on the east side booms’ surface cell at 2019’s winter solstice.

![Graph showing direct irradiance](image)

**Figure 6.15**: Direct Irradiance (W m⁻²) received by the cell at 2019’s winter solstice, referent to the boom’s east sides

Considering the already explained 270° azimuth angle, together with the −3° tilt angle, the graphics for the incident sunlight angle and direct irradiance can be subsequently observed in figures 6.16 and 6.17 for the west side of the booms. Again, with the 180° discrepancy from the east faces, the sunlight will only focus on these cells by early afternoon, more specifically, at 2 pm.
Figure 6.16: Sunlight’s incident angle (°) on the west side booms’ surface cell at 2019’s winter solstice.

Figure 6.17: Direct Irradiance (W m\(^{-2}\)) received by the cell at 2019’s winter solstice, referent to the boom’s west sides.

All these previously illustrated and described graphics concerned the external variables that, although they may affect the energy output the cell will have, by means of the reduction of the irradiance, they do not condition or influence the cell internal operation and subsequently its efficiency. Of the constant parameters heretofore characterized only the series resistance, the shunt resistance and the cell temperature have an impact in the cell efficiency.

Varying the load resistance \(R_{\text{load}}\), the COMSOL Multiphysics application obtained the I-V and P-V curves illustrated in figures 6.18 and 6.19, from where the maximum power point, \(I_{\text{sc}}\) and \(V_{\text{oc}}\) were
extracted. The efficiency was determined with the referred parameters and the provided solar cell area of 25 mm (50 mm long x 0.5 mm narrow), obtaining a value of 17.92 %, based on equation 6.4.

Figure 6.18: I-V curve of the solar cell with voltage (V) on the horizontal axis and current (mA) on the vertical axis.

Figure 6.19: P-V curve of the solar cell with voltage (V) on the horizontal axis and power (mW) on the vertical axis.

Ideally, for a perfect solar cell, the shunt resistance would be infinite, preventing the power losses due to the creation of a current alternative path, reducing the voltage and the current flowing through the cell. Shunt resistance effect are especially severe at low light levels and at lower voltages. Contrarily, the optimal for the solar cell is achieved with a zero series resistance, indicating perfect cables, contacts and semiconductors, that would not exert a semblance of resistance to the current passage. Its effects are particularly noted in the fill factor - neither affecting the open circuit voltage not the short circuit current -, which decreases with the increase of the series resistance.
Crossing this provided information with the modeled curves, the effects of both resistances are noted. If the series resistance was equal to zero, the I-V curve presented in figure 6.18 would decrease almost instantaneously, with little variation of voltage, from the maximum power point to the open circuit voltage. Instead, the voltage decreases more slowly, reducing the fill factor. For the same curve, the effect of the shunt resistance is also recognized. Without its presence the current value would remain almost constant from the low voltages until the maximum power. These factors are reflected in the efficiency of the cell, that instead of the maximum value of nearly 20% for the technology, is here about 17.92%.

6.3 Total Output Power Estimate

The previously computed I-V and P-V curves were determined for one isolated solar cell, with 25 mm² (50 mm x 0.5 mm) of area. In order to ascertain the total output power, the number of cells that fit in the considered structures need to be calculated. In appendix A, the vehicle measurements are discriminated, so, with resource to it, the amount of photovoltaic cells is pinpointed. Each wing has a total length of 1009 mm and a width of 278 mm - excluding the aileron -, where, a line of 20 cells can be made at length and column 556 at width, composing a total of 11,120 cells, that conceive a singular wing panel. For one face of the boom, the length is 503 mm and the width 45 mm, therefore, a line of 11 cells and a column of 90 cells can be made, forming a panel of 990 cells.

With the number of cells of each panel calculated, the connections are shaped, thus, permitting the settlement of the voltage and current values. It was decided with the number of cells in mind, to associate the column cells in parallel, with the link between different columns being a series connection, both for the wings and boom’s faces. These connections will show its effects in the current and voltage, as expected, with the parallel bonds augmenting the current in each point proportionally to the number of lines and the series bonds having the same effect on the voltage, which will increase proportionally to the number of columns.

Due to the possibility of disability a solar cell can face, either by natural causes creating shading or electronic malfunctions, there is a need to use bypass diodes to guarantee that the failure of one cell does not inhibit the operation of the whole panel. These devices are usually placed between parallel connections so that the deficiency of a cell is not spread between different series connected groups. The bypass diodes were not here considered as its inclusion in the theoretical study would not make any difference, with neither shading nor failure being taken into account.

Simulating the coverage of one wing with solar cells generated the I-V curve illustrated in figure 6.20 and the P-V one exhibited in figure 6.21 with 556 parallel connected lines and 20 series connected columns, constituting a 278 000 mm² photovoltaic panel.

As consequence of the difference between the incident irradiance on the boom’s opposed faces, it
was decided that the analysis would be made separately for each. Consequently, figures 6.22 and 6.23 manifest the I-V and the P-V curves, respectively, for a boom face, with 90 parallel connected lines and 11 series connected columns, shaping a panel 24752 mm² total area.

Both the I-V curves of the wing (figure 6.20) and boom face (figure 6.22) derived from the singular cell one (figure 6.18), and the same for the respective P-V curves. Being constituted by series and parallel connections of the already presented silicon solar cell, the panels have merely an increase in the voltages and currents, nonetheless counting with the same characteristics. On that manner, the efficiency maintains itself the same as the single photovoltaic cell, cutting the need to make any further calculations.

Finally, to have an estimation of the generation of the solar panels for 40 min (UAV’s time of flight), considering the maximum and minimum presented cases, the direct irradiance graphics were analysed
in order to find the 40 min period with maximum irradiance. The "brute force" method was used, and with resource to it, it was concluded that the maximum production was from 13 h30 min to 14 h10 min, where both the boom’s sides panels were producing energy and the irradiance incident on the wings reached its peak. Having the wings the highest area, it was natural that its production would be more important to the results. As aforementioned, the [UAV] usually flies between 10 h and 16 h, so, this extreme hours were also taken into account. To calculate the total direct irradiance received by the panels over the considered times, the area of the concerning part of the graphics was determined, using a linear regression, a valid approximation due to the reduced period of time in consideration.

Having the irradiance, the efficiency and the area of the panels, the generation - a product of the three -, was calculated. For the longest summer day, having the unmanned vehicle a 0° azimuth angle and −3° tilt angle, mimicking the best conditions, the produced energy for a flight at 10 am is 27.95 W h, at
the maximum hour production, 69.49 Wh are obtained and 40 min before 16 pm is 32.98 Wh. Emulating the worst conditions, the shortest winter day with the UAV flying in a 180° azimuth and the same tilt angle, the produced energy was 5.40 Wh at 10 am, 21.50 Wh at the maximum hour production and 9.17 Wh at 15:20 pm.

As aforementioned, the unmanned vehicle uses two batteries, one for the motor and the other for the "payload". Both are Li-Po with 3.7 V of nominal voltage, being the contrast in the number of batteries. Due to the motor higher consumption, its battery is composed by 10 cells connected in series with a 10 A·h capacity, while the battery for the components counts with a reduced number of 3 cells, likewise connected in series, with a 5 A·h capacity. In total, the motor battery has a stored energy of 55.5 Wh, while the other has 370 Wh.

The system UAV plus payload will need to stop either by the run out of the motor battery or the run out of the components battery, although this do not mean both the batteries will always be discharged. The consumption of energy highly depends on the payload height, mission, and type of flight, however, for the payload battery, the medium consumption is usually inferior to 2 A - which with the 5 A·h capacity can last up to two and a half hours - , indicating that the time of flight is shortened by the discharging of the motor battery. In this case the appropriate decision is to connect all the solar panels only to the motor battery, so that the maximum time of flight can be achieved. In this assembly only one Maximum Power Point Tracker (MPPT) is needed to connect between the batteries and the panels, to ensure the optimization of the battery charging.

Knowing the motor drains up a 370 Wh battery in 40 min, the calculations of the augmented time of flight with the solar panels, for each case, is simple. On the ideal summer day, the panels can give the unmanned aerial vehicle an extra time of flight between 3 min (the minimum produced at 10 am) and 7 min 30 s (the maximum energy produced by the panels). For the worst winter day, the values are much more discouraging, varying between 35 s and 2 min 19 s.

CIAFA besides a fully electric UAV has another type with hybrid configuration, strictly speaking, a gasoline motor with only one battery feeding the components. If needed, the panels can also be applied to this vehicle, feeding only the payload battery.
Conclusions

Contents

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7.1 Achievements

The main goal of this thesis was the analysis of the inclusion of solar photovoltaic panels in the augment of the UAV time of flight. To achieve that an intensive study of the available photovoltaic technologies was made, in order to determine the most suitable solution to the problem specific conditions. The ordinary installation of the solar panels is at roofs, the grand majority never passing the 100 m limit, intrinsically, the surrounding variables that may affect its performance are evaluated considering that height. Due to the vehicle flying altitudes between 200 m and 2000 m - with reference to the sea level -, the results of the interactions between the surrounding nature and the solar cells needed to be re-evaluated, this time, counting with its possible variation with altitude.

A theoretical assessment of the wind flow, pressure, irradiance and cell temperature was made. For the wind flow and resulting pressure there was a possibility of its values affecting the integrity of the solar cell, thus invalidating its usage. For this reason, a study was made with resource to COMSOL Multiphysics Turbulent Flow module, which aims to solve the Navier-Stokes set of equations by modeling the fluid domain around the airflow, as a mesh of discrete elements. The generated simulations allowed to conclude that even in these extreme conditions the resulting pressure was not enough to cause fracture or other damage.

With the hypothesis of breaking discarded, an appraise of the operation of the to be included solar panels was the next step. It was made with a COMSOL Multiphysics application, using both the Ray Optics and the Semiconductor modules to produce as output the characteristics of the incident light as well as both the I-V and P-V curves. Subsequently, considering the incident irradiance, the panels area and efficiency, values between 35 s and 2 min 19 s for the worst conditions, and for the best conditions an interval from 3 min to 7 min 30 s, were obtained for the augment of the time of flight. While seven minutes is almost a quarter of the total time of flight, thirty five seconds is not even considered an augment. This gap of values highlights the instability of the small scale solar panels installations, which due to its reduced area, can not always rely on the use of solar panels. Here the direction of flight is also an extra problem, as it conditions the incidence angle. Due to the sensibility to weight of the UAV an appropriate solution would be coating the vehicle with solar paint, however that is still a technology in development. Despite these conclusions, the inclusion of the solar panels can not be viewed as bad, for in its best case it can rise the time of flight for seven and a half minutes.

7.2 Future Work

This study accrues from one of the UAV's major problems: the autonomy. It served a theoretical purpose of analyzing the inclusion of solar photovoltaic panels in the augment of the UAV time of flight. Although results were here achieved, there are still different directions to take when future work is considered.
While the solar cells chosen as preferred were flexible silicon, the other second generation ones with higher or equal efficiency were still viable to be used in this work, despite having toxic elements in its composition. The influence of the parameters would need to be theoretically accounted, for its effect is not equal in all the solar cells. After, a comparative study of the efficiencies should be made.

Despite having the theoretical efficiency of the cells, the next approach to the problem could be the determination of the augmented time of flight practically. Flexible silicon solar cells could be implemented on the UAV structure, connected to the motor battery and the extra time of flight by them provided ascertain in this manner. Various days with different climate conditions should be taken into account.
Bibliography


Aerial Vehicle Area Calculation

The area calculations of the UAV were based on the aerial vehicle plans provided by CIAFA and Military Academy. Along with the measurements, a lateral and a top view were included - figure A.1. Solely the parts that can be covered by sun the majority of the day without being shaded (superior plan), were considered in the area. There were some approximations made, as there were insufficient measurements for the real area calculation, namely the wings as a rectangular surface.

The areas were divided in sections as the cells are to be applied in each individually. In equation A.1 the superficial area of one wing was determined. It was necessary to remove the ailerons from the calculus as they need to stay mobile and therefore can’t be covered by solar panels.

\[
A_{\text{wing}} = 330 \times 1009 - A_{\text{aileron}} = 330 \times 1009 - 52 \times 1009 = 280\,502 \text{ mm}^2
\] (A.1)

Next, the stabilizers were considered for panel placing. However, associated with the vertical and horizontal stabilizers are the rudders and the elevator, respectively, which are the control surfaces that therefore need to be mobile during flight. Besides that, the stabilizers are sensible parts of the UAV whereupon the extra weight, even if it is not a substantial value, can cause centering problems in the
aircraft. For the enunciated reasons the placing of panels on the stabilizers needs to be well pondered, being the reason why it was discarded for this part of the work and left for later consideration.

The last structures in which cells will be applied, are the "bands" connecting the body of the vehicle and the stabilizers, denominated booms. The area of one boom is presented in equation A.2

\[ A_{\text{boom}} = 2 \times (45 \times (878 - 325)) = 49770 \text{ mm}^2 \] (A.2)

For the total available area were summed the previous determined areas, considering two wings and two booms, as it can be seen in equation A.3. The obtained value was approximately 0.66 m².

\[ A_{\text{total}} = 2 \times A_{\text{wing}} + 2 \times A_{\text{boom}} = 660544 \text{ mm}^2 = 0.670604 \text{ m}^2 \] (A.3)
Air Pressure Formula Deduction

In this appendix the deduction of the formula regarding the dependence of the air pressure with height will be made. An arbitrary gas column with area section $S$ and height $h$ is envisioned to facilitate. The starting point is the pressure equation in which the force will be replaced by Newton’s first law where $m$ is the air mass and $g$ the gravitational air constant. Taking into account the cross sectional area volume $V = hS$ and considering the air mass as a function of its density $\rho$ and volume, equation (B.1) is achieved.

$$P_{hs} = \frac{F}{S} = \frac{mg}{S} = \frac{\rho g h S}{S} = \rho gh$$  \hspace{0.5cm} (B.1)

As the pressure is described in function of the height, a variation of the pressure implies that a variation of the height had to occur. In light of the diminish of the pressure with the augment of the height, the minus signal appears at equation (B.2).

$$dP_{hs} = - \rho gdh$$  \hspace{0.5cm} (B.2)

If the atmospheric air is viewed as an ideal gas, the ideal gas law can be used to express the density through pressure:
\[ PV = \frac{m}{M} RT = \frac{m}{VM} RT \Leftrightarrow \rho = \frac{MP}{RT}. \]  

Combining equations B.2 and B.3 a differential relation for \( dP_{hs} \) is obtained.

\[ \frac{dP_{hs}}{P_{hs}} = -\frac{Mg}{RT_{hs}} dh \]  

Integrating the relation B.4 the barometric formula is presented at equation B.5, where \( P_{hs} \) and \( T_{hs} \) are the pressure and temperature at the desired height \( h \). Furthermore the rest of the parameters are constants, \( M = 0.02896 \text{ m s}^{-2} \) the molar mass of the air, \( R = 8.3143 \text{ N m mol}^{-1} \text{ K}^{-1} \) the universal gas constant and \( g = 9.807 \text{ m s}^{-2} \) the gravitational acceleration.

\[ \int \frac{dP_{hs}}{P_{hs}} = -\int \frac{Mg}{RT_{hs}} dh \Leftrightarrow \ln P_{hs} = -\frac{Mg}{RT_{hs}} h + \ln C \Leftrightarrow P_{hs} = C \exp \left( -\frac{Mg}{RT_{hs}} h \right) \]  

To finalise the expression, the constant \( C \) can be determined recurring to an initial condition \( P(hs = 0) = P_0 \), being \( P_0 \) the pressure at sea level. Also, height \( h \) can be simplified as \( h_s - h_0 \), the subtraction of the height at bottom of the boundary layer in the considered place to the desired height. The final form of the barometric formula can be seen at equation B.6.

\[ P_{hs} = P_0 \exp \left( -\frac{Mg}{RT_{hs}} (h_s - h_0) \right) \]
Reynolds Average Navier-Stokes
Equations

The Computational Fluid Dynamics is a field whose work is based in the use of computational assessment techniques to solve the Navier-Stokes set of equations. As it was aforementioned, for this work the Reynolds-Averaged Navier-Stokes (RANS) method will be the considered, therefore the transformations it brings on the Navier-Stokes are explained in this appendix.

Starting with the already presented Navier-Stokes set of equations,

\[
\begin{align*}
\rho \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) &= -\nabla p + \nabla \cdot \left[ \mu \left( \nabla \mathbf{u} + (\nabla \mathbf{u})^T - \frac{2}{3} (\nabla \cdot \mathbf{u}) \mathbf{I} \right) \right] + \mathbf{F} \\
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) &= 0 \\
\rho &= \rho(p,T)
\end{align*}
\]

(C.1)

that count with the fluid density \( \rho \), the fluid pressure \( p \), the fluid dynamic viscosity \( \mu \), the identity tensor \( \mathbf{I} \) and the fluid velocity \( \mathbf{u} \), which can be further decomposed in fluid velocity for the x-component \( u \), y-component \( v \) and z-component \( w \). As already stated, for a chaotic flow, the velocities have both a time averaged component and a turbulent fluctuating time dependant component, as described by...
expressions $C.2$

$$\begin{align*}
u(t) &= u(t) + u'(t) \\
v(t) &= v(t) + v'(t) \\
w(t) &= w(t) + w'(t)
\end{align*}$$  

(C.2)

Navier-Stokes first equation represents the conservation of moment, composed by the inertial forces

$$\rho \left( \frac{\partial u}{\partial t} + u \cdot \nabla u \right),$$

the pressure forces $-\nabla p$, the viscous forces $\nabla \cdot [\mu \left( \nabla u + (\nabla u)^T - \frac{2}{3} \left( \nabla \cdot u \right) I \right)]$ and lastly, the external forces applied to the fluid $\mathbf{F}$. When an incompressible flow approximation is considered, the continuity equation - Navier-Stokes second equation $\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$ yields

$$\nabla \cdot \mathbf{u} = 0 \Rightarrow \frac{2}{3} (\nabla \cdot \mathbf{u}) = 0.$$  

(C.3)

Furthermore, the study will use a stationary analysis, which signifies the annulment of the inertial forces first term $\frac{\partial \mathbf{u}}{\partial t}$. After these simplifications, the Navier-Stokes system assumes the form illustrated by equations $C.4$

$$\begin{align*}
\rho (\mathbf{u} \cdot \nabla \mathbf{u}) &= -\nabla p + \nabla \cdot [\mu \left( \nabla \mathbf{u} + (\nabla \mathbf{u})^T \right)] + \mathbf{F} \\
\nabla \cdot \mathbf{u} &= 0 \\
\rho &= \rho(p, T)
\end{align*}$$  

(C.4)

After applying the RANS method (time averaging) to $C.4$ Navier-Stokes set of equations, a further decomposition of the velocities and pressure is made to simplify the equation concerning the conservation of moment, resulting in equation $C.5$

$$\rho \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -\nabla p + \nabla \cdot [\mu \left( \nabla \mathbf{u} + (\nabla \mathbf{u})^T \right)] + \mathbf{F}$$  

(C.5)

The external forces $\mathbf{F}$ applied to the fluid are not subjected to turbulent fluctuations, as such, $\mathbf{F} = F$. Also, since the time averaging of a fluctuating value is considered zero, $\langle \mathbf{f}' \rangle = 0 \Rightarrow \frac{\partial \mathbf{f}'}{\partial x} = 0$, and the time-average of a variation of a mean value is the variation of the mean value $\frac{\partial \mathbf{f}}{\partial x} = \frac{\partial \mathbf{f}}{\partial x}$, equation $C.5$ can be further simplified in equation $C.6$

$$\rho \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -\nabla p + \mu \left( \frac{\partial^2 \mathbf{u}}{\partial^2 x} + \frac{\partial^2 \mathbf{u}}{\partial^2 y} + \frac{\partial^2 \mathbf{u}}{\partial^2 z} \right) + \mathbf{F}$$  

(C.6)

Recurring to simple calculus transformations, equation $C.6$ can be further decomposed for its three directions. Considering that, equations $C.7$, $C.8$ and $C.9$ present the RANS form for the x, y and z directions, respectively.
\[\rho \left( \frac{\partial \mathbf{u}}{\partial x} + \frac{\partial \mathbf{v}}{\partial y} + \frac{\partial \mathbf{w}}{\partial z} \right) = \frac{\partial \mathbf{p}}{\partial x} + \mu \Delta \mathbf{u} - \rho \left( \frac{\partial u' v'}{\partial x} + \frac{\partial v' v'}{\partial y} + \frac{\partial w' v'}{\partial z} \right) + F_x \] (C.7)

\[\rho \left( \frac{\partial \mathbf{u}}{\partial x} + \frac{\partial \mathbf{v}}{\partial y} + \frac{\partial \mathbf{w}}{\partial z} \right) = \frac{\partial \mathbf{p}}{\partial y} + \mu \Delta \mathbf{v} - \rho \left( \frac{\partial u' v'}{\partial x} + \frac{\partial v' v'}{\partial y} + \frac{\partial w' v'}{\partial z} \right) + F_y \] (C.8)

\[\rho \left( \frac{\partial \mathbf{u}}{\partial x} + \frac{\partial \mathbf{v}}{\partial y} + \frac{\partial \mathbf{w}}{\partial z} \right) = \frac{\partial \mathbf{p}}{\partial z} + \mu \Delta \mathbf{w} - \rho \left( \frac{\partial u' w'}{\partial x} + \frac{\partial v' w'}{\partial y} + \frac{\partial w' w'}{\partial z} \right) + F_z \] (C.9)

The system of equations composed by C.7, C.8 and C.9 can always be converted back to tensor form, as illustrated in equation C.10. It is of utmost importance to accentuate the appearance of the term \( \rho \mathbf{u}' \mathbf{u}' \), named Reynolds stress. Apparent turbulent shear stress or, as already said, Reynolds stress, results from the time-dependent fluctuations that are not solved by the time-averaging method.

\[\rho (\mathbf{u} \cdot \nabla \mathbf{u}) = -\nabla \mathbf{p} + \mu \Delta \mathbf{u} - \nabla \cdot (\rho \mathbf{u}' \mathbf{u}') + F \] (C.10)

By the use of \( k - \epsilon \) turbulence model, the Reynolds stress is modeled into \( \mu_1 (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) - \frac{2}{3} \rho k \mathbf{I} \), where \( \mu_1 \) is the turbulent viscosity and \( k \) the turbulent kinetic energy. From the previous demonstrated manipulations, the final simplified form for the RANS conservation of moment equation can be achieved, as seen in C.11, which is integrated in the RANS system of equations C.12.

\[\rho (\mathbf{u} \cdot \nabla \mathbf{u}) = -\nabla \mathbf{p} + (\mu + \mu_1) \Delta \mathbf{u} - \frac{2}{3} \rho k \mathbf{I} + F \] (C.11)

\[
\begin{align*}
\rho (\mathbf{u} \cdot \nabla \mathbf{u}) &= -\nabla \mathbf{p} + (\mu + \mu_1) \Delta \mathbf{u} - \frac{2}{3} \rho k \mathbf{I} + F \\
\nabla \cdot \mathbf{u} &= 0 \\
\rho &= \rho(p, T)
\end{align*}
\] (C.12)