MAR-HAB

Mars
Hot Air Balloon

L. Wheeler

Discussing the requirements of future astronauts on Mars
and providing a flying vehicle to aid in exploration.

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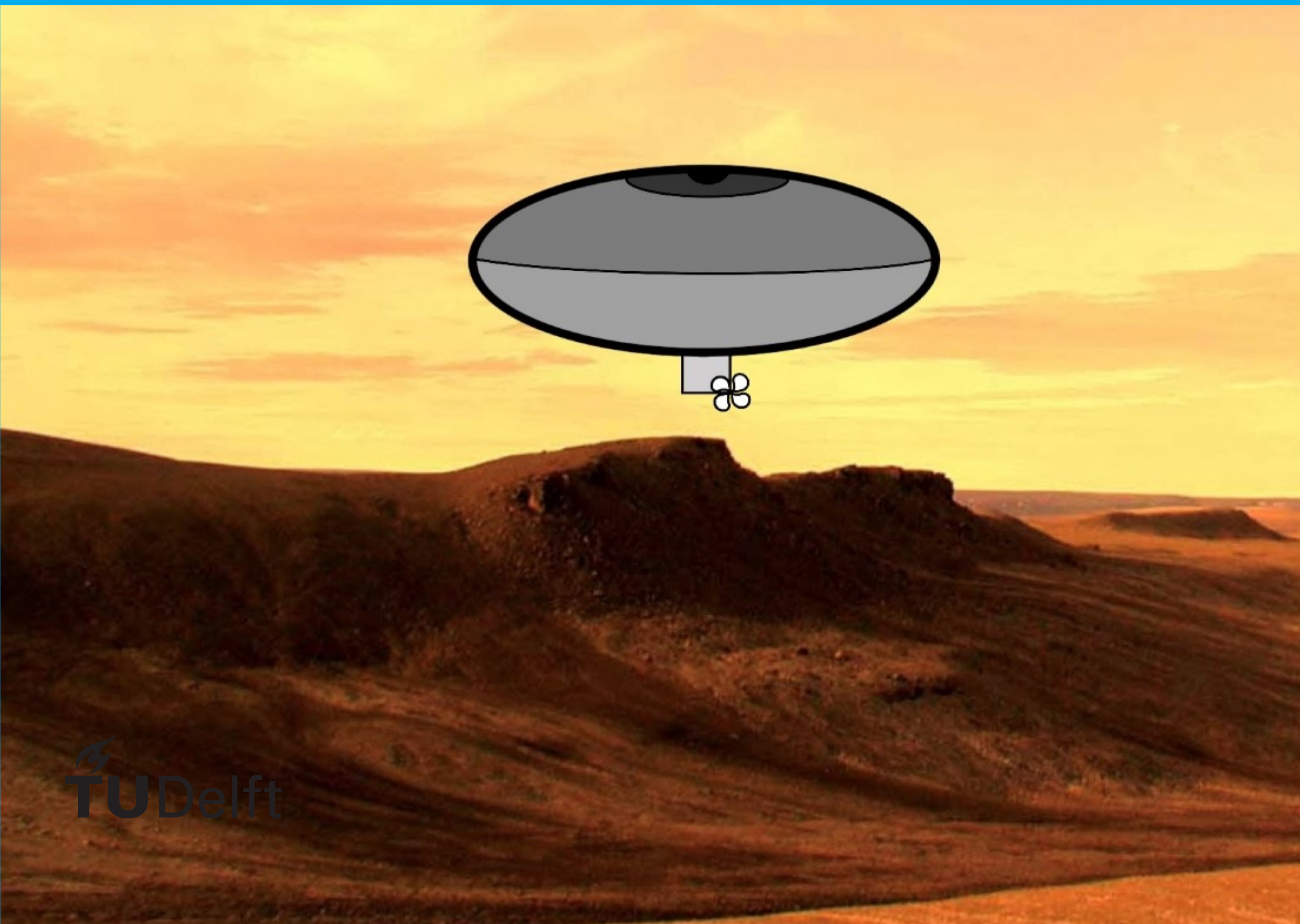

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Mars
Hot Air Balloon

by

L. Wheeler

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Preface

I would like to use this opportunity to thank my parents, all four of them, for the opportunity and support throughout the years. I believe that without their support I would not have had the opportunity that has lead me to this position and also not be the man I am today. All of their support has allowed me to be able to finish a Master's degree in Space flight.

I would also like to thank Elise, my girlfriend, for having the patience to deal with me and Luna throughout these years which has definitely helped make the Master's degree much easier. I feel that without her positive energy, that my negative start to the Master's thesis would have delayed my progress even longer.

Lastly, I would like to thank my supervisors. Originally, this thesis had the goal of focusing on flapping wing vehicles for Mars but due to unfortunate circumstances, I was not able to do this anymore. However, both Alessandra and Daphne still allowed me the opportunity of looking at a more general topic. Furthermore, they have helped me greatly in understanding what my mistakes were and what I could do to improve, which will help in the future.

L. Wheeler
Delft, June 2020

Abstract

Human exploration on Mars is nearing actualisation and the space industry is therefore in need of vehicles with the capability of transporting goods and exploring the surrounding area. Current Mars rovers by NASA, such as the Curiosity, provide excellent researching capabilities from a remote location. However, these land based drones are slower and less manoeuvrable around obstacles than airborne vehicles would be. Due to the need of transportation and exploration, this report aims to get acquainted with current research on Mars flight and provide a preliminary design concept enforced by the following mission goal:

”To aid future Mars colonists by providing a feasibility study of a flying vehicle capable of carrying a predetermined payload.”

To approach this goal, it was decided to determine which flying vehicle concept would be the most optimal in a Martian atmosphere via a trade-off analysis. Four options were considered and a balloon was deemed more optimal for a Martian environment compared to aircraft, rotorcraft and flapping wing vehicles. The main reasons for this are that the balloon is the most power efficient and is a design that provides the least amount of risk concerning likelihood of failure and safety of astronauts.

Thereafter, the process required to design a hot air balloon and the programming of the code is described. Results indicate that a balloon with a prolate ellipsoid shape is optimal with the ratio between the minor and major axis being 0.41, therefore resulting in a balloon with a major axis radius of 33.8 m and a minor axis radius of 13.86 m. A surface area of 131.58m^2 is selected for the flexible solar cells which have been calculated to be able to power a two propeller system ensuring that the balloon can counter headwinds of up to 15 $\frac{m}{s}$. Finally, to ensure altitude control is possible, a venting system is applied on the top of the balloon ensuring a venting volume of 117 m^3 is possible. This is enough to ensure the balloon can land, take-off and control its altitude as desired.

This thesis is therefore able to provide an initial design for a Mars exploration balloon capable of controlling not only its altitude but also its position. This is achieved by using the solar energy to increase the balloon’s temperature and a vent area of 19.03 m^2 to control this temperature. All this provides a design that can be controlled and meets the versatility requirement as it is capable of carrying a variety of heavy payloads and fly past ground obstacles.

Contents

Nomenclature

α	Absorptivity coefficient	$-$
ϵ	Emmisivity coefficient	$-$
$\epsilon_{combined}$	Average emmissivity due to various coatings	$-$
ϵ_{first}	Emmissivity of first coating	$-$
ϵ_{second}	Emmissivity of second coating	$-$
$\eta_{efficiency}$	Thrust efficiency	$-$
$\frac{dV}{dt}$	Altitude acceleration	m/s^2
$\rho_{A_{material}}$	Surface density of envelope material	g/m^2
ρ_{atm}	Atmospheric density	kg/m^3
ρ_{gas}	Balloon gas density	kg/m^3
ρ_{power}	Power density of the solar cells	W/m^2
$\rho_{solarcell}$	Surface density of solar cells	g/m^2
σ	Stefan-Boltzmann constant	J/m^2sK^4
a	Radius of shorter, minor axis	m
A_{first}	Area of first coated surface	m^2
$A_{frontal}$	Cross sectional area as seen from the front of the balloon	m^2
A_{second}	Area of second coated surface	m^2
$A_{solarcell}$	Solar cell area	m^2
$A_{surface}$	Total surface area of balloon envelope	m^2
A_{top}	Cross sectional area of balloon from above	m^2
c	Radius of longer, major axis	m
C_D	Drag coefficient	$-$
C_L	Aerodynamic lift coefficient	$-$
$C_{P_{atm}}$	Heat coefficient of atmospheric gas	W/m^2K
C_{P_g}	Heat coefficient of balloon gas	W/m^2K
C_P	Heat coefficient	J/K
$C_{virtual}$	Virtual mass coefficient	$-$
D	Drag force	N
dt	Time differential	s
F_{lift}	Lift Force	N

F_{Net}	Net force generated	N
g_{Mars}	Mars' gravitational acceleration	m/s^2
H	Balloon altitude	m
h	Convective heat transfer coefficient	W/m^2K
H_n	Newly calculated altitude	m
H_p	Altitude from previous simulation loop	m
m_{cells}	Mass of a single solar cell	g
$m_{envelope}$	Envelope mass	kg
m_{extras}	Mass of extra equipment	kg
m_{gas}	Mass of balloon gas	kg
m_{in}	Mass of gas entering from below	kg
M_m	Molar Mass	g/mol
$m_{payload}$	Payload mass	kg
m_{total}	Total mass	kg
$m_{virtual}$	Virtual mass	kg
N_{cells}	Number of cells per square meter	$-$
P	Pressure	Pa
P_0	Surface pressure	Pa
P_{atm}	Atmospheric pressure	Pa
P_{in}	Power into the system	W
P_{out}	Power out of the system	W
P_{thrust}	Thrust Power	W
P_{total}	Total Power	W
$Pa_{dynamic}$	Dynamic pressure of a wind stream	Pa
Pa_{static}	Static pressure of a wind stream	Pa
Pa_{total}	Total pressure of a wind stream	Pa
R_a	Specific gas constant	$m^3Pa/Kmol$
S_{area}	Wing surface area	m^2
S_{ratio}	Prolate shape ratio, a ratio of minor divided by major axis	$-$
T	Temperature	K
T_0	Surface temperature	K
T_{atm}	Atmospheric temperature	K
T_g	Gas temperature	K
T_{new}	Updated temperature in simulation loop	K

Th	Thrust force required	N
V_{ascent_n}	Newly calculated ascent speed	m/s
V_{ascent_p}	Ascent speed from previous simulation loop	m/s
$V_{Balloon}$	Volume inside the balloon	m^3
$V_{e_{flow}}$	Vent flow velocity	m/s
$V_{outflow}$	Volumetric outflow of the balloon via the vent	m^3/s
$V_{required}$	Required volume to provide lift equal to the weight of the balloon	m^3
V_{wind}	Wind speed	m/s
Ve	Flight speed	m/s
W_{total}	Total weight	N

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Glossary

BADS Buoyant Aerobot Design and Simulation. 1

ESA European Space Agency. 1

ESS Expert System: Settlement. 22

GRC Galactic Cosmic Rays. 34

LTA Light Than Air. 19

MAVLab Micro Air Vehicle laboratory. 1

MCD Mars Climate Database. 3

MOLA Mars Orbiter Laser Altimeter. 21

NASA National Aeronautics and Space Administration. v

RTG Radio-isotopic Thermal Generator. 20

SEP Solar Energetic Particles. 34

TRL Technology Readiness Level. 13

TU Technical University. 8

V&V Verification and Validation. 40

1 Introduction

Mars is the fourth planet from the Sun and is one of the closest neighbouring planets. Common questions in science fiction and research are: Was there life on Mars? Is Mars habitable? and lastly, What happened to Mars? Finding the answers to these questions compels scientists to explore Mars. ESA states that answering the question about life on Mars is one of the main reasons to visit the red planet [9]. These questions have yet to be answered, mainly due to the extreme conditions on the planet.
On Mars, the average surface pressure is 700 Pa compared to that of Earth at 101,325 Pa. This is due to the atmosphere having an extremely low density that is 1/100 th of Earth's [10][24]. The temperature on the red planet is also highly fluctuating, ranging generally from 190 K to 250 K or -83 to -23 degrees Celsius, in one location throughout a single day [10][24]. Furthermore, Mars has a weaker atmosphere and magnetic field than Earth, resulting in insufficient protection against radiation, which is harmful to both humans and electronics.
All aspects considered, the environmental conditions on Mars are that of a dangerous and isolated desert.

Current research and exploration of Mars include eight operational missions, including satellites, and multiple missions planned for the future [31]. However, land based rovers are limited to a relatively slow speed and the areas that can be visited are limited by the rough surface. This is where a flying vehicle can benefit exploration. Other than landing and take-off, the vehicle would not be constrained by rough or uneven surface and will have the ability fly across terrain filled with boulders and rocks. A flying vehicle would therefore be beneficial to future Mars exploration but naturally presents many issues.

There are many reports that provide excellent knowledge and discuss various flying concepts for other planets. The thesis BADS, Buoyant Aerobot Design and Simulation, provides a detailed description of different balloon types and covers most of the aspects required whilst also providing a computational code to design balloons [34]. To introduce the topic of balloons on other planets, reports [14] and [13] provide a strong starting position to understand the main points of ballooning in a Martian atmosphere. Balloons on other solar system objects, such as Venus and Saturn's moon Titan, have already been tested or designed. On Venus, for example, the VEGA balloons have provided large amounts of detailed measurements of Venus' atmosphere [30]. On Titan, a mission has been described using a hot air balloon heated by a Radio-isotopic Thermal Generation [19].

As far as ornithopters are concerned, the book The DelFly, from TU Delft's own Micro Air Vehicle laboratory, MAVLab, provides some of the most recent information regarding flapping wing flight, due to the MAVLAB's exceptional concepts and expertise [7]. Other reports of ornithopters, such as [3], give outstanding information of ornithopter aerodynamics, as well as rotorcraft, and provide a validated comparison between both. Sources on aircraft information are more readily available compared to the other three.

This thesis aims to dive into the possibilities of a flying vehicle on Mars and provide an initial design that will be able to overcome the limitations of current mars rovers.
This will be done by looking at the need statement and providing a result that complies with the following mission goal:

”To aid future Mars colonists by providing a feasibility study of a flying vehicle capable of carrying a predetermined payload.”

The format of the report, is as follows. Chapter 2 will introduce background information while Chapter 3 will introduce the need statement for this work and the requirements that are imposed onto the design. In Chapter 4, four concepts that are likely candidates for flight on Mars will be discussed and the most feasible concept is chosen. This is achieved by selecting five criteria; Technological Readiness, Power, Manoeuvrability, Cost and Risk. As each criteria is weighted in order of importance, the concept with the highest rating is deemed the best one for use on Mars. With the type of flying vehicle chosen, determining a suitable landing position is important and therefore, Chapter 5 will introduce various positions and the requirements imposed on the landing site. This allows for atmospheric conditions to be fixed, allowing the next two designing chapters to have most of the variables set. Chapter 6 will begin by explaining the equations and processes required for the initial design. After which it will go into more depth by simulating the flight profile, following similar methods to [34] and will discuss the changes necessary in the simulation findings to meet the altitude goal. To continue work in this subject, Chapter 7 will describe some recommended next steps. Lastly, Chapter 8 will conclude the thesis and summarise the details of the final design.

2
Background Information

Mars is the fourth planet from the sun. Also known as the red planet, it is often wondered whether life has thrived on the surface in the past. However, it is currently uninhabitable to life as we know it due to the harsh atmospheric conditions. The red planet has a gravitational acceleration of around 3.71 m/s^2 on the surface. This is almost a third of force experienced on Earth, as the average gravity here is roughly 9.81 m/s^2. This is due to the planet being smaller than Earth, having a radius of only 3390 km compared to Earth which has a radius of 6371 km [18].
Before going into the atmospheric conditions, there is an important variable that needs explanation, named the Solar Longitude, which is used in all figures that come from the Mars Climate Database, MCD. The MCD is a program created in collaboration with ESA to simulate various conditions on Mars. A web interface of the MCD is provided to allow many variables, such as the pressure, temperature, wind and dust conditions, to be simulated throughout an entire Martian year. According to the MCD, "the Solar Longitude Ls is the Mars-Sun angle, measured from the Northern Hemisphere spring equinox where Ls=0." [10][24]. This is used to depict the season and the current Mars position relative to the Sun.

Having introduced the solar longitude, the atmospheric conditions can be explored. Atmospheres play an important role in determining the lift force that any of the flying concepts can create. Figure 2.1 shows how the surface density changes along the surface of Mars on the 1st of January 2020 on the 12th Martian hour [10][24].

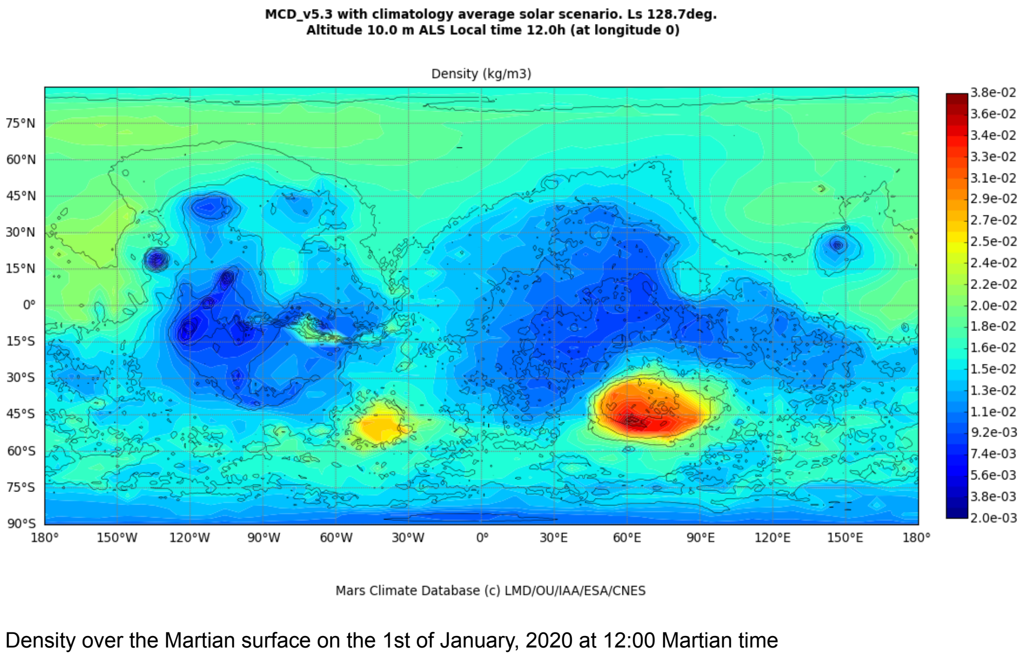

Figure 2.1: Density over the Martian surface on the 1st of January, 2020 at 12:00 Martian time

It is clear that the density levels across the Martian surface can vary significantly. For example, locations such as 45' South, 60' East and 50' South, 45' West, higher densities are expected, most likely due to a lower elevation. Furthermore, to get a clear understanding of how the seasons affect the density, Figure 2.2 shows the change in density over an entire Martian year at the location of 0' North and 0' East. The graph plots the daily density values at 12:00 hour Martian time.

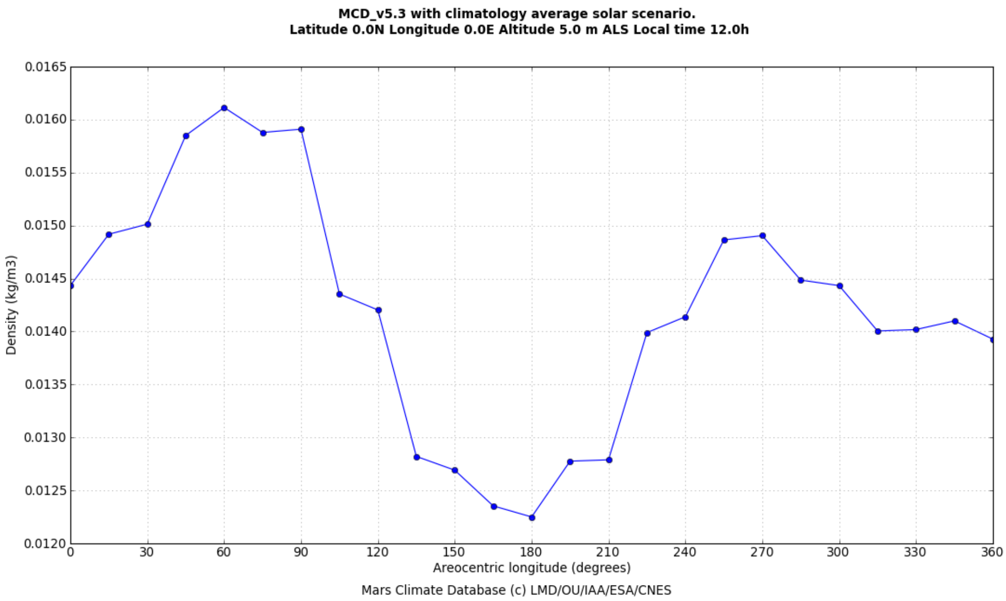

Figure 2.2: Yearly change in density at a location of 0' North and 0' East, representing each day at 12:00 local time

Figure 2.2 correlates with the seasons as described by the MCD. The MCD states that at a solar longitude of 0, the spring equinox of the northern hemisphere occurs [10][24].. The density, at this location, slowly increase throughout this season. At a solar longitude of 90', the northern hemisphere's summer solstice occurs begins. It can be seen in Figure 2.2 that the density decreases throughout the summer season. This density decrease stops at a Solar Longitude of 180'. These changes in density are possible due to the density being a function of the temperature and pressure as defined by the Ideal gas law.

$$\rho = \frac{PM_m}{R_a T} \tag{2.1}$$

where: ρ = Density ($\frac{kg}{m^3}$)
P = Pressure (Pa)
M_m = Molar mass ($\frac{kg}{mol}$)
R_a = Specific gas constant ($\frac{m^3 Pa}{Kmol}$)
T = Temperature (K)

The average values for the pressure and temperature are 700 Pa and 215K, respectively [25]. This is definitely low when compared to the Earth atmosphere with a pressure of 101325 Pa and an average temperature of 25 degrees Celsius, which is equal to 298.15 K.

In addition to the variables described above, there are multiple different aspects that also need to be considered throughout this work. These are the solar, wind and dust effects on the atmosphere. Firstly, the amount of solar energy is smaller when compared to Earth's atmosphere. Generally, in low orbit around Earth, a solar power constant of 1400 W/m^2 is assumed for temperature calculations. However, on Mars, the average solar constant at the surface is assumed to be 500 W/m^2 [18]. Secondly, wind and dust conditions on Mars are complicated to visualise in a graph at a single moment as these depend on the season and time of day. The MCD, however, provides initial assumptions on the conditions by using simulations and data collected during previous missions.

Figure 2.3 shows the MCD's representation of the entire Martian surface and the wind conditions on the 1st of January 2020 at 12:00 Earth time. This correlates to a solar longitude of 129 degrees, representing summer for the northern hemisphere and a dust free season. [10][24]. It is seen that on this particular time, the wind conditions vary between 0 and 22 m/s. This gives a brief but clear overview to show that low wind speeds are definitely possible.

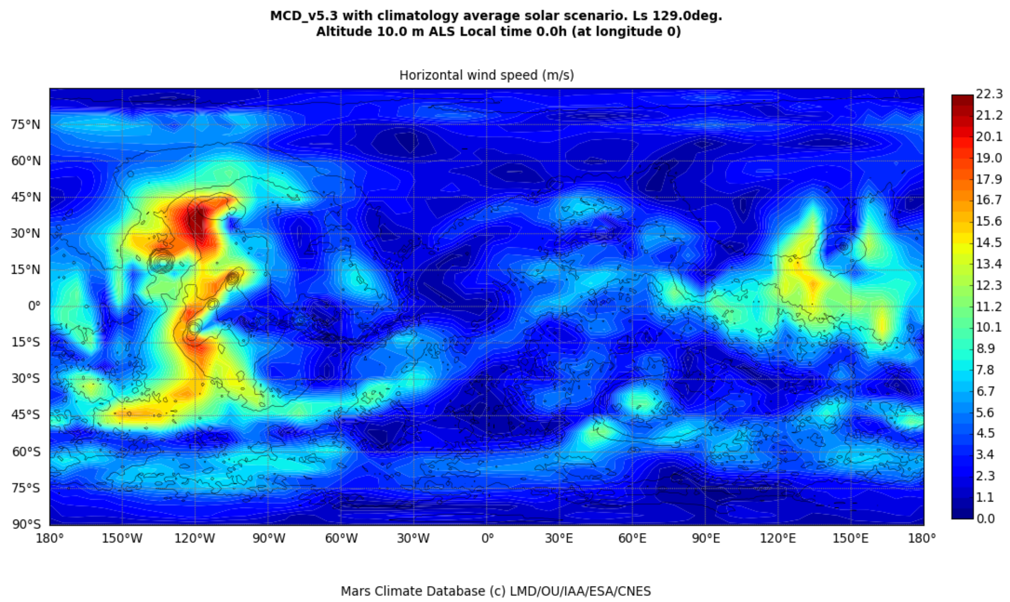

Figure 2.3: Wind across the entire Martian surface at surface level according to the Mars Climate Database [10][24]

The final complication on Mars is the significant amount of dust. The dust particles are relatively small which are able to cause problems for spacecraft. Main areas that are affected by Martian dust are moving components and solar cells [23]. Furthermore, the any dust in the atmosphere will impact atmospheric conditions, for example increasing the surrounding gas temperature.

Lastly, to give an initial impression of locations with a higher dust deposition on the 1st of January 2020 at 12:00 Earth time, Figure 2.4 is given. Figure 2.4 is simulated on the same time as the previous wind figure. The figure shows that dust accumulation depends on location but what is also important is to consider the measurement time. On Mars there are seasons that are more dusty, suitably named the Dusty seasons. These occurs between the solar longitudes of 180' up to 360' [10][24]. This is half of the Martian year.

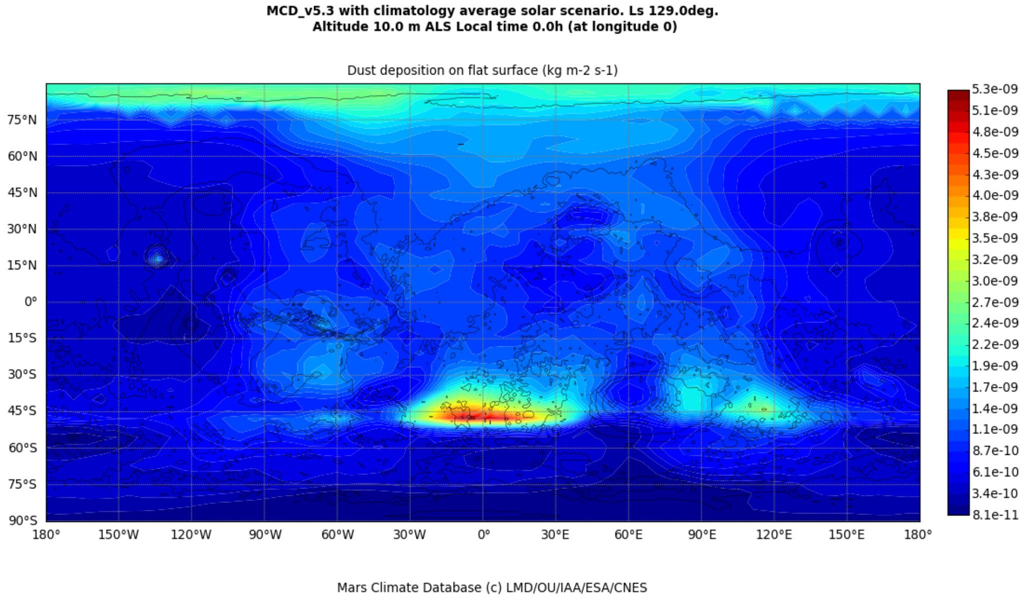

Figure 2.4: Dust across the entire Martian surface at surface level according to the Mars Climate Database[10][24]

To understand the impact of these seasons, Figure 2.5 shows the yearly change at a location of 0' North and 0' East of each Martian day at 12:00. This figure clearly shows the large variations in dust gathering on a flat surface. There is a 50% increase in dust gathering between the peak and the begin of the dust season, at 180' solar longitude. The impact of the dust season is apparent, describing the minimum point being less than a third of the peak dust gathering. From this it can be concluded that there are seasons throughout the year that offer better conditions regarding dust buildup.

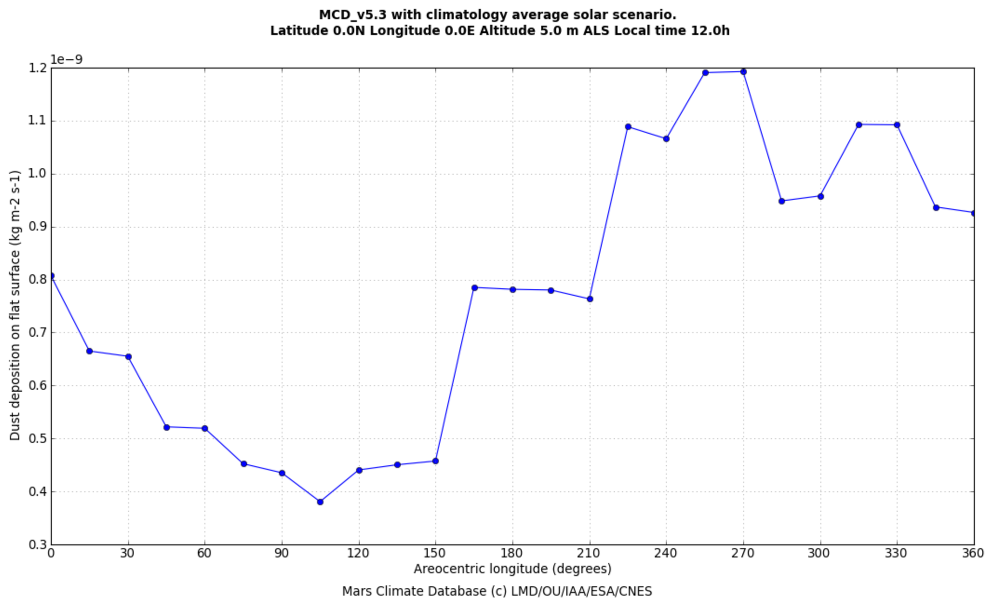

Figure 2.5: Yearly change in dust gathering on a flat surface at a location of 0' North and 0' East, representing each day at 12:00 local time [10][24]

To conclude, the conditions on Mars are not ideal for flight. The calculations still remain the same as on Earth but the values will differ. Furthermore, the difference in atmospheric conditions between Earth and Mars requires careful consideration in choosing a settlement site and a preliminary design.

3 Mission Description

This chapter provides the discussion regarding the need and mission statements that describe the mission and its objective. Understanding the objective and goal of the mission allows stakeholders to be determined and requirements to be imposed on the system.

3.1. Mission Goal

As preparation for this thesis, a literature study was conducted focusing mainly on flapping wings and the changes required for flight on Mars. Due to the growing interest of Martian colonisation, it became apparent that knowledge of the Martian atmosphere and more importantly, its surface, is becoming increasingly vital. Current land rovers have been successful in their missions, however, their lack of manoeuvrability is limiting potential research sites as a large amount of terrain is currently off limits.

Need Statement
”Future Mars colonists will need to explore and gather resources in the surrounding environment without being obstructed by the rough terrain.”

With the Need Statement defined, a Mission Statement can be provided which will guide the entire thesis.

Mission Statement
”This thesis will provide a preliminary flying vehicle design capable of navigating at a determined Mars settlement site.”

To be able to provide this concept, the mission goal was devised to be:

Mission Goal
”To aid future Mars colonists by providing a feasibility study of a flying vehicle capable of carrying a predetermined payload.”

3.2. Stakeholders

Stakeholders are the parties that will affect and be affected by the design which in this case, will be thought of as a flying aerial vehicle.

3.2.1. Active Stakeholders

With a system completed, active stakeholders are parties that will interact with the final design after it has landed on Mars. The following list describes potential stakeholders.

- Scientific community

- Mars Astronauts

Mars is relatively unknown as of yet, and therefore, any measurements and information gathered by the flying vehicle will benefit others in their work. This makes the scientific community an active stakeholder as they would actively be interacting with information from the flying vehicle on Mars.
Another aspect that affects the thesis is the amount of available research and resources. If little to no research has been made regarding Mars flying vehicles, more time will be spent researching and verifying new aspects. Whilst, in the opposite case, more time can be spent collecting information and using available research to provide an optimal design. Therefore, the extent of this thesis relies on the science community and what has been done in the past.

Also, a final active stakeholder that deserves a mention is that in the near future, there will be astronauts on Mars trying their best to colonise the desert terrain that is Mars. When the time comes, these astronauts would most likely need tools and equipment, some of which are heavy and need lifting. The flying vehicle would be able to help in that aspect. Furthermore, the purpose of this thesis is to provide a flying vehicle that will be used by astronauts on Mars, making them active stakeholders.

3.2.2. Passive Stakeholders

Passive stakeholders, compared to active ones, do not interact with the design but rather, affect the success of it. This can be achieved by constricting certain aspects or providing support.

- TU Delft
- Interplanetary Regulations
- Space Agencies

At the time of writing, this thesis is a small part of the Master of Space Engineering at the TU Delft. Therefore, the university will play a major part in the success as it constrains the time and money available for this project.
There is no actual time constraint, as the student decides the planning. However, the planning must be kept realistic and therefore, the original six months that the thesis is meant to take will act as a time constraint. Furthermore, the manufacturing and testing of the flying vehicle would most likely be outside the cost constraint that the university provides to Master students. This will affect the work and the report.

Humans have not yet visited other planets or colonised anything in space, however, there are already interplanetary regulations that aim to protect other celestial bodies. An example would be planetary protection regulations from the Committee of Space Research. These regulations would most likely affect the preparation and sterilisation of the payload and design.

Lastly, the final passive stakeholder is regarded as the space agency, or private company, that helps move the vehicle to Mars. The launcher and launch aspects are not considered in this report, but it must be noted that space companies that provide launcher capabilities are passive stakeholders.

3.3. Requirements

The first step after determining the Need Statement and stakeholders is to summarise the constraints. All of the finalised requirements are listed below and fall under three categories. Stakeholder, Control and Environmental requirements.
The stakeholder requirements are the constraints on the preliminary design based on the needs of the stakeholders. Therefore, the requirements in this category are based on what the stakeholders, mostly the active ones, would want the preliminary design to achieve during its mission. For example, a simple but important need is that the flying vehicle be able to fly to the given target location.
The control requirements provide the required aspects that are needed to ensure that the vehicle is capable of controlling itself while on Mars. These are all requirements that are based on the research conducted during the literature study. However, the payload requirement is set to 100 kg because it is

deemed necessary that the flying vehicle be capable of carrying payloads that astronauts themselves would not be able to. Lastly, the environmental requirements are based on the research in Chapter 5. In this chapter, the needs of future astronauts are discussed and used as requirements for the design.

Stakeholder requirements

- MFD-SH-1: shall be able to land on command
- MFD-SH-2: shall be able to take-off on command
- MFD-SH-3: shall be able to fly to a target location
- MFD-SH-4: shall be able to communicate with the operator
- MFD-SH-5: shall make use of a renewable energy source

Control Requirements

- MFD-CTL-1: shall have a mechanism capable of stabilising the vehicle at the target design altitude of 200 m
- MFD-CTL-2: shall have a mechanism to provide thrust equivalent to the highest expected drag
- MFD-CTL-3: shall be able to carry 100 kg
- MFD-CTL-4: shall contain a method to reduce dust build up
- MFD-CTL-5: shall be able to achieve flight for a minimum of one hour

Environmental Requirements

- MFD-E-1: Latitude shall be between 50' North and 50' South
- MFD-E-2: Elevation shall be below 2 km MOLA
- MFD-E-3: Site shall have less than 8% rock abundance
- MFD-E-4: Average steady wind speed shall be less than 15 $\frac{m}{s}$
- MFD-E-5: Maximum peak winds shall be less than 30 $\frac{m}{s}$
- MFD-E-6: Site shall have a minimum of 5% weight percentage of water concentration
- MFD-E-7: Flying vehicle shall be designed for a target altitude of 200 m

3.3.1. Killer Requirements

To determine whether the preliminary design succeeds at meeting the requirements, a few killer requirements are selected. The chosen key requirements are shown below:

- MFD-SH-5: Shall make use of a renewable energy source
- MFD-CTL-1: Shall have a mechanism to control altitude
- MFD-CTL-3: Shall be able to carry 100 kg
- MFD-E2: Elevation shall be below 2 km MOLA
- MFD-E6: Site shall have a minimum of 5% weight percentage of water concentration

The first requirement, MFD-SH-5, is chosen as a killer requirement to ensure that the design can sustain it's own power without relying on the astronauts. This will prove beneficial in times of limited power.

Requirements MFD-CTL-1 and MFD-CTL-3 are control requirements imposed on the design and provide the main criteria to determine whether the preliminary design can carry the target payload while being controllable, and therefore, safe for the astronauts to use.
These are chosen as killer requirements as the safety of the Mars colonists is the most important aspect of any flying vehicle. Also, the goal of the design is to fly with the predetermined payload of 100 kg. If this is not possible, the design does not meet its goal and is therefore considered a failure.

The last two, MFD-E-2 and MFD-E-6, are chosen instead of other environmental requirements as these two will narrow down the possible choices for a settlement site which not only has beneficial atmospheric conditions but also provides a water concentration necessary for astronauts to thrive. The other environmental requirements are also important but do not constrain the settlement site as much as MFD-E-2 and MFD-E-6.

4

Concept Trade-Off

With the stakeholders and requirements defined in the last chapter, the main parameters and constraints of this thesis have been defined. Considering these, a selection must be made out of the available concepts: a balloon, ornithopter, aircraft or a rotorcraft. The concepts must be weighed against one another and the strongest candidate chosen. This chapter describes the method used for the trade-off.

4.1. Concepts

Before starting the analysis, each of the concepts is introduced to give a clear impression of the discussion.

4.1.1. Balloons

The first human flight in a balloon was achieved in 1783 by the Montgolfier brothers [20] . This feat was achieved using a hot air balloon in which the gas inside the envelope, or thin film, was heated by a fire. Since then, many other methods to achieve flight have been discovered. To understand how a balloon can generate lift, one must look at the following equation.

$$F_{lift} = g_{Mars} V_{Balloon} * (\rho_{atm} - \rho_{gas}) \tag{4.1}$$

where: F_{lift} = Net lift force (N)
g_{Mars} = Mars Gravitational acceleration ($\frac{m}{s^2}$)
ρ_{atm} = Atmospheric gas density ($\frac{kg}{m^3}$)
ρ_{gas} = Balloon gas density ($\frac{kg}{m^3}$)
$V_{Balloon}$ = Volume of gas inside balloon (m^3)

Equation 4.1 is Archimede's law of buoyancy which describes two main variables that affect the lift force generated: the volume and density difference between the gases in the atmosphere and balloon. Density is related to the pressure and temperature via the Ideal Gas Law. As an example, the hot air balloon flown by the Montgolfier brothers had a constant volume. The brothers achieved flight by lowering the gas density inside the envelope by heating the gas.

It is also possible to generate lift without an on-board power source, which is a beneficial situation for Mars. This can be achieved by a pressurised gas inside the envelope or rather, a hot air balloon powered by the sun. These two examples decrease the power requirement for lift-off drastically. However, balloons will most likely be large in size, causing inherent problems such as control and stability.

4.1.2. Ornithopters

An ornithopter achieves flight by flapping its wings, thus mimicking flight in nature. The first recorded ornithopter is from 1871, where an engineer created a toy that flapped wings and achieved flight. However, this was merely powered by a rubber band and could not fly longer than a few seconds [5].

It was not until recently, that flapping wing vehicles were being designed with electric motors. This is only made possible because the manufacturing industry is capable of providing miniature components such as wings and motors. An example of a flapping wing design, the DelFly, is shown in Figure 4.1 [7]. Figure 4.1 shows a design with a wingspan of 10 cm and a tail. This is not necessarily the case for every flapping wing design, as proven by the newest ornithopter in the DelFly series, the DelFly Nimble which is designed without a tail.

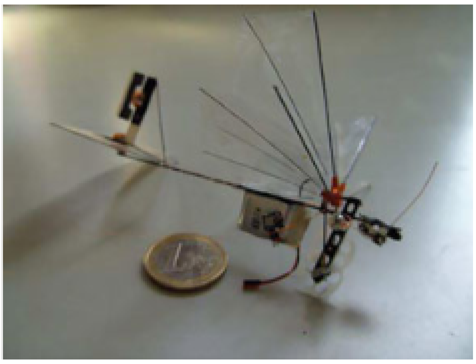

Figure 4.1: The DelFly design

To conclude the ornithopter section, flapping wing vehicles can have a variety of forms and can perform accurate manoeuvres. The future of ornithopters will have some beneficial purposes. However, these type of vehicles have not had extensive testing outside of controlled environments.

4.1.3. Airplane

In 1903, the Wright brothers managed to fly the first motorised airplane. They achieved this historical landmark as they were able to provide an engine with a higher power to weight ratio. With this new engine, less lift was required and thus, the small double winged airplane could take off. The equation for the lift force is shown in Equation 4.2.

$$F_{lift} = \frac{1}{2}\rho_{atm}C_L S_{area} Ve^2 \tag{4.2}$$

where: F_{lift} = Lift force (N)
ρ_{atm} = Atmospheric gas density ($\frac{kg}{m^3}$)
C_L = Lift coefficient ($-$)
S_{area} = Wing surface area (m^2)
Ve = Flight speed ($\frac{m}{s}$)

The main parameters in Equation 4.2 are the wing surface area and the flight speed. Due to the low atmospheric density on Mars, an airplane would need to fly fast or have a larger wing surface area. The advantage of controlled and accurate flight manoeuvres, however, is most likely replicated on Mars as well.

4.1.4. Rotorcraft

Rotorcraft use propellers or rotors to provide lift. The rotors allow for a high manoeuvrability during landing and take-off, enabling a vertical motion. Rotorcraft is a vague term as it includes concepts such as a helicopter or quad copters. Each have their benefits and own goals that they succeed at. Whilst a broad concept, rotorcraft are used in many different scenarios.

Rotorcraft are stable vehicles able to manoeuvre in a controlled manner. This advantage can most likely be replicated on Mars. However, due to Equation 4.2, the rotors will have to rotate at higher speeds, or have a larger rotor surface area. Having the blades be longer or faster might cause structural problems and endanger to the astronauts on the surface.

4.2. Criteria

As the mission goal in Chapter 3 states that a flying vehicle is needed, the trade off criteria must help decide on the proper choice. To do this, a selection of criteria is provided and discussed. This is done in the next few sub chapters. Each concept will be given a rating between 1 and 5 for each of the discussed criteria. Where 1 represents the worst value and 5 the best. With all these ratings applied, a weighing factor is applied to each design criteria in order to represent the more important ones. This will then be input into a table and shown in the results section. The list of criteria used is:

- Technology Readiness
- Power
- Manoeuvrability
- Cost
- Risk

4.2.1. Technology Readiness

In order to categorise each concept in different Technology readiness levels, TRL, it must be noted that there are nine different levels. These were originally determined by NASA and later adapted throughout other space agencies [22]. These depend on the maturity of the technology in question. The following list of nine technology readiness levels are taken from NASA themselves [21]

- TRL 1 - Basic principles observed and reported
- TRL 2 - Technology concept and/or application formulated
- TRL 3 - Analytical and experimental critical function and/or characteristic proof-of concept
- TRL 4 - Component and/or breadboard validation in laboratory environment
- TRL 5 - Component and/or breadboard validation in relevant environment
- TRL 6 - System/subsystem model or prototype demonstration in a relevant environment (ground or space)
- TRL 7 - System prototype demonstration in a space environment
- TRL 8 - Actual system completed and “flight qualified” through test and demonstration (ground or space)
- TRL 9 - Actual system “flight proven” through successful mission operations

To determine the best candidate for a Mars mission, the extent of the research and testing that is currently available for each concept will be compared. This will help determine which concept is most ready to fly on Mars and provide an initial design that can spark a next generation of Mars exploration vehicles.

4.2.2. Power

This criterion will determine which of the concepts is most power efficient by looking at the following aspects:

- Power required for lift generation
- Length of flight time

The ability to recharge batteries is an important aspect of distant missions. However, because astronauts will be using the concept, it can be assumed that the astronauts will take care of any required recharging of the batteries. This also means that safe storage from storms and dust can be assumed. Therefore, this criteria will regard power consumption to achieve flight as the main point. This is chosen because a design with a large power requirement will either drain the astronaut’s power supply or require a method to achieve this power.

4.2.3. Manoeuvrability

The manoeuvrability criteria will compare each concept and the available control mechanisms. To do this, two aspects will be discussed. These are shown below:

- Ability to take-off and land
- Speed and accuracy of turning

Firstly, whether the concept will be able to land and take-off is an important consideration. The ability to land shows that a vehicle is capable of controlling it's altitude whilst using information from its sensors, or landing system, to perform the manoeuvre. Landing is important to ensure that the vehicle can be stored safely and that interaction with astronauts, after mission completion, is possible.

The second aspect is to discuss and compare the speed and accuracy that each concept is capable of providing during a control manoeuvre. Accuracy is important for a design but whether the manoeuvre takes a few seconds, or a few hours, changes the outcome of the manoeuvre. This criteria will determine which of the concepts provides the best control of its position in all axes.

4.2.4. Cost

The cost of a design is an important criterion for investors to consider starting a project. This criterion will look into certain aspects of the design and discuss their potential influences on the price tag. Cost will be split into two sections:

- Mass
- Number of moving parts

Mass is crucial for the cost criterion as it plays a key role in a number of cost based aspects. Firstly, a heavier mass that needs to go to Mars costs significantly more. Furthermore, a larger mass most likely leads to requiring a stronger lifting force, which affects the power requirement.

Each concept will also require a certain amount of moving parts. However, manufacturing moving parts for Mars will include additional research and work as these must withstand the atmospheric conditions and the dust present on Mars. More moving parts in a design will lead to a more complicated manufacturing process and therefore, a higher cost. There is no requirement that constrains the cost but keeping the design as cheap as possible is good practice as a cheaper project provides more incentive to continue.

4.2.5. Safety

Space missions are usually costly endeavors and therefore, it is important to understand that there is always a risk involved. The safety criterion will help determine the concepts with the least amount of risk. To do this, three aspects will be discussed:

- Component Failure
- Complexity
- Astronaut Safety

The first aspect is the component failure. This will consider the scenario in which one or multiple key components have failed. For example, one of the rotors of a rotorcraft fails and cannot provide lift. Does the rotorcraft crash or can it continue with the remaining rotors? Questions like this will provide the comparison for this criteria. The component failure can be split into two categories;

- Likelihood
- Consequence

For comparing the concepts, each failure discussed in the results chapter will be compared to others with the likelihood and consequence of failure in mind. A failure that is extremely unlikely to occurs but with minor consequences is not as severe as the opposite. Also, the more complex a design is, the more components there will be. This leads to a higher risk factor which is a good way to compare multiple concepts. The last aspect that requires consideration is the safety of astronauts.

4.2.6. Weighting Factors

With all of the criteria described, it is crucial to add a weighing factor to determine which are more important. Before discussing various criteria, the weighing factor can have values of one, two or three, with three indicating the highest importance.

It is assumed that the manoeuvrability criterion is the most important. This relates to the need to be able to perform manoeuvres, such as take-off and landing, and being able to accurately control the vehicles position. An uncontrollable vehicle has a higher chance of unforeseen events, such as crashing into a mountain or boulder. Furthermore, the vehicle would present a danger to any astronauts close by. This relates to the safety of the concept. Astronaut safety is crucial to the mission and a concept with a higher likelihood of injuring astronauts should be given the appropriate criterion value. To this end, the safety of the mission is given a three for the weight factor.

The technology readiness levels are important to dictate whether a concept is ready for a mission. However, it is less important than the safety of astronauts and whether it can be controlled. Therefore, a weighing factor of two is considered for this criterion. The power criterion is mainly used to determine whether a concept is capable of achieving flights longer than an hour and whether it is possible to provide the power necessary for the concept. Whilst power is a design aspect, it is not the main factor affecting the design and is therefore given a weight factor of two.

The lowest grade given to a criterion is a one. This is chosen for the least important criterion for the trade-off which is the cost of the concept. Cost naturally plays a key role in many missions, however, since this thesis is focusing on the designing aspect, there is no mission cost requirement. Therefore, whilst it is still important to consider, the cost of a concept is not a limiting factor in this trade-off.

4.3. Trade-Off Matrix

Table 4.1: Trade-off Results

Criteria	Balloon	Ornithopter	Aircraft	Rotorcraft	Weight Factor
Technology Readiness	4	2	3	3	x2
Power	4	2	2	3	x2
Manoeuvrability	3	4	3	4	x3
Cost	2	2	4	2	x1
Safety	3	1	2	2	x3
Total	36	25	29	32	

Table 4.1 shows the results for the trade-off analysis. It is found that a balloon offers the best results. The following section will discuss the reasoning for each value in the table. This is done by looking at each individual concept in the following order; Balloons, Ornithopters, Aircraft, Rotorcraft.

4.3.1. Technology Readiness Discussion

Regarding the TRL, it can be said that balloons have the most flight experience on other planets due to the VEGA balloons on Venus. [30]. Furthermore, there are many reports such as [14] and [19] which have dedicated time researching possibilities of balloon flight on other planets. Therefore, the balloon concept is given a value of four for the Technology Readiness criterion. A five is not given as this would imply a concept that has been tested in Martian conditions.

On Earth, electrically powered ornithopters are becoming increasingly more popular but regardless, are still the newest of all concepts. Therefore the TRL of this concept is lower. The aerodynamics involved in flapping wing flight are complex and not perfectly understood, especially when compared to the flight of balloons and aircraft. However, there are some reports which discuss minor changes required for flight on other planets such as [29] and [4]. To this end, the ornithopters are given a value of two for the Technology Readiness criterion.

Aircraft, on the other hand, have been extensively researched since the first flight in 1903. There are reports researching the possibility of aircraft in other atmospheres, such as [17] which provides a theoretical design of a Venus aircraft. Current aircraft are reliable and backed by years of experience, however, flight in a different atmosphere has not occurred. Therefore, this concept can not have the same Technology Readiness criterion as the balloons and is given a value of three.

Rotorcraft also generalises a widely used form of flight, with multiple rotors. Even though this form of flight is efficient and very manoeuvrable, it is also given a value of three for the technology readiness. The concept is proven by the experience of flight on Earth, similar to aircraft. However, a rotorcraft concept has yet to be flown in an atmosphere on a different planet and therefore, is graded lower than the balloon concept.

4.3.2. Power Discussion

For balloons, the lifting force does not require an additional power source. Lift will either be provided by a pressurised gas in the balloon, or via heating of the insides. Naturally, the heating can be done with a power source on board the balloon, but it is assumed that this would be an ineffective method due to the large volume that must be heated. The balloons will require a form of altitude and positional control mechanisms. However, an example for altitude control is a simple vent used to discharge gas [14]. Lastly, balloons generally achieve long flight times, as can be seen on Earth and this feature is also expected on Mars. Therefore balloons are given a value of four for thie criterion.

Current ornithopters, such as the DelFly Nimble can only fly for a limited amount of time. For example, the Nimble can fly autonomously up to five mins [15]. This represents an issue already as the battery cannot sustain long flight and the requirement for minimum flight time for this mission is one hour. Obviously, this is caused by the miniaturisation of components in order to create a light weight flapping wing vehicle. The power required to generate lift is more likely less than the aircraft and rotorcraft concepts mainly due to the smaller vehicle. Therefore, a value of two is given for the power criteria mainly due to the low flight times that are achieved with flapping flight.

Aircraft on Earth are able to fly for hours, transporting passengers on ten, or more, hour long flights. Smaller airplane drones are also capable of long flight times. However, the power requirement to achieve lift is the highest amongst all concepts. On Mars, it is expected that flight speeds will be much greater, which can be seen in Equation 4.1. Here, the density is drastically lower as described in Chapter 2 and therefore requiring a higher velocity. Therefore, the combination of long flight times with a high power consumption results in a value of two given for the aircraft concept.

Lastly, the rotorcraft concept flies differently than the previous concepts mentioned. Rotorcraft achieve flight with vertically pointed rotors and by either shifting its center of mass or by rotating different propellers at various speed. This method of flight does not require as much power as aircraft do and it is possible for current rotorcraft to achieve long flight times. Therefore, the rotorcraft concept is given a value of three for the power criteria.

4.3.3. Manoeuvrability Discussion

The manoeuvrability of a concept on Earth will not specify exactly how a concept will be able to manoeuvre in the Martian atmosphere. However, by looking at flight on Earth, a general idea of a concept's control and accuracy can be described.

First off, a balloon is most likely the least manoeuvrable concept. A balloon has the ability to land and take off, especially without significantly complicated mechanisms. This is a benefit that only the balloon concept can provide which helps its score. However, when regarding the speed and accuracy of performing manoeuvres, a balloon falls short. Extra equipment would need to be placed on the balloon to be able to manoeuvre or counter any winds. This could be in the form of pumps, wings or propellers. Many options exist, which again, is a benefit. But none of these ideas will provide the balloon with a high speed or accuracy. This is because the size of the balloon also plays a role. A larger object requires a stronger force to move and rotate due to moment of inertia. With all this in mind, the balloon is given a three for this criterion. This is because the concept can land proficiently but might lack some position control.

Out of all designs, the newly designed ornithopters are showing improved accuracy and control with the DelFly Nimble being able to mimic the flight of a fruit fly [15]. Furthermore, the testing and data for these designs is done in a controlled environment. Mars has a harsh atmosphere with wind speeds that will significantly influence the ornithopter and affect the accuracy and perhaps, make landing more complicated than in a controlled environment. Therefore, this concept is given a value of four.

An aircraft or flying wing is able to control its trajectory and turn, given that control mechanisms exist. The ability to land, however, is trickier. A landing strip will be needed to safely land. It's possible that landing and take-off can be helped with a roll able landing strip placed by the astronauts, for example. Hence, this concept is given a value of three for manoeuvrability.

Rotorcraft make use of multiple rotors to provide lift, which rotate at different speeds and directions to create a stable platform. Since rotors are propellers that point vertically, rotorcraft have the capability of landing and taking off vertically and therefore can choose where to do so. This allows the concept to have a safe and stable landing which is crucial for a safe landing amongst astronauts. Furthermore, controlling its position and turning accordingly can be done accurately. This concepts is therefore given a value of four for the manoeuvrability, similar to the ornithopters.

4.3.4. Cost Discussion

Balloons provide lift due to a density difference with the atmosphere. The smaller this difference, the larger the volume required to compensate. Hence, any balloon on Mars would surely have a large radius. With increasing size, the material will get more expensive. Furthermore, depending on the type of balloon, additional gas might be needed to be sent along with the balloon, making the trip more costly. With all of this in mind, this concept is given a two for this criteria.

Without providing a preliminary design, it is complicated to give a general cost estimate as the size of the ornithopter might vary greatly. However, the size will surely be less than the balloon's radius. Also, the design must be as lightweight as possible to ensure flight is possible, especially with a payload. So far, this should cost less than the balloon. However, flapping wings is a result of many mechanisms moving, as seen in Figure 4.1, which must be made specifically for the design. Hence, this concept is given a value of two for this criterion.

The mass of the aircraft is dependent on a number of factors in the design. For example, if the aircraft is designed to fly at a low speed, the wings are required to have a larger wing span, this is seen in Equation 4.2. This would result in a heavier design. Whilst for the opposite, smaller wings are required but a stronger thrust source is needed. Without doing detailed calculations, it would be hard to determine exactly which would have a larger effect on the mass. However, the amount of components needed for aircraft is less than both the ornithopter and rotorcraft concepts. Therefore, a value of four was given for the aircraft concept.

Naturally, on Earth the mass of rotorcraft can be kept at a minimum. However, this concept might have to scale up its size to compensate for the change in conditions. Even if this is the case, the mass should not be too extreme and keeping the costs relatively low. However, the number of rotors in this design will vary depending on the requirements, but will most likely include multiple. Since multiple rotors are likely, more components are needed on this design when compared to aircraft. Due to this, a value of two was given for this criterion.

4.3.5. Safety Discussion

Out of all four choices, balloons are the only concept that can achieve lift without any moving components and are the least complex method of flight. However, one major design aspect, the envelope of the balloon, is important. There is a low likelihood of envelope failure, such as a tear in the material.

But if the situation does arise, the consequence is high because flight will not be possible anymore. Balloons, however, are safest for the astronauts amongst all concepts due a lower amount of fast rotating components or wings. The balloon can still be dangerous, for example, when a large balloon is inflated and the wind force is strong. Then there is a possibility that the balloon is pushed into an astronaut, even though the chance is minimal. To this end, a value of three is given to the ballooning concept.

Considering the risk aspect of a design, ornithopters seem like the most vulnerable concept. Not only are these creations highly complex in terms of aerodynamics and control, these concepts have barely shown practical experience on Earth. Most of the flying, so far, seems to be done in controlled lab environments due to the newly experimenting of the complicated aerodynamics involved. Therefore, the complexity of this concept is the highest out of all four.

Furthermore ornithopters make use of small electric motors to power to wings through a series of connections. All of these components are light weight and interconnected. Therefore, if any of the connections, or even the motors, fail or malfunction, the entire flight and control of this concept is affected. This means that the consequences are high. And since it is unknown how these concepts will fly in a windy atmosphere, let alone a dusty one, it can easily be said that the likelihood of an aspect going wrong is also quite significant. Lastly, as the ornithopters are generally smaller than other concepts, these pose the least danger to the astronauts. This is further emphasised due to fast rotating propellers, or rotors, being replaced by light weight flapping wings. Regardless, this concept has the highest mission risk compared to the other three. This results in ornithopters receiving a value of one for safety.

Aircraft is another concept that is complicated to manufacture but with all the models and experience available, it is not complex. Since the only difference in the generation of lift for aircraft is most likely the density difference between Earth and Mars, other aspects will be similar. Aircraft, due to the moving components, such as propellers, have a higher likelihood of failure due to the harsh Martian environment, such as dust. If components that rely on movement to function fail, the consequence is high. Furthermore, whilst aircraft are generally stable and can be controlled there is still a risk to the safety of astronauts. Large wings and fast moving propellers are not components that astronauts want near by. All included, this concept accounts for some risk but is not as risky as the ornithopters in terms of component failure and complexity. Therefore, a value of two is given.

Rotorcraft is an odd concept as it is not entirely complex but there are many aspects to it. Firstly, the components that are most likely to fail are the rotors. The rest of the body can technically be encased in a body, offering extra protection. Therefore, the more rotors a design has, the more failure points are possible. However, because of a larger amount of rotors, any one failure will have less consequence. For example, if a design with one rotor is created, that single rotor failing will end the mission. Whilst, a quad copter, with four rotors, will still be able to have some form of control with the remaining three rotors. However, whilst the concept is generally stable, the rotors pose a danger to the astronauts. As mentioned in the introduction of the rotorcraft concept, these rotors will most likely need to be larger or rotate faster. These can pose a risk to any nearby astronauts. Therefore, this concept is also given a value of two for the risk criteria.

4.3.6. Conclusion

Each of the concepts has been thoroughly researched and discussed up to his point. Taking all criteria into consideration, the clear outcome of this trade-off is that balloons will be the most versatile and power efficient design. Furthermore, each of the four concepts use different methods to provide lift and balloons have the most simple method, buoyancy. By utilising Archimedes' law of buoyancy, lift is generated which can be controlled by numerous methods, such as temperature and volume control. Rotorcraft is the second place winner whilst aircraft and ornithopters follow in third and fourth place, respectively. To reach this conclusion, each criteria was thoroughly researched and discussed in the previous sections. Making sure that personal opinions and choices did not influence the trade-off represented one of the tougher tasks of this chapter. However, the trade-off is completed and states that balloons are the best option.

4.4. Design Option Tree

With the balloon concept being the winner of the trade off analysis as seen in Table 4.1 and the fact that the balloon has many different types of providing lift, a design option tree is created to narrow down potential candidates. Balloons generate a lifting force by having a lower density than the atmosphere. Therefore, a few key aspects affect the flight of a balloon. This includes the gas inside the envelope, the temperature and pressure difference between the gas and the atmosphere surrounding the balloon. Hence, various designs can be used which target different variables that provide lift. According to [2],the various types can be categorised into four sections which are also known as Light than Air vehicles, or LTA.

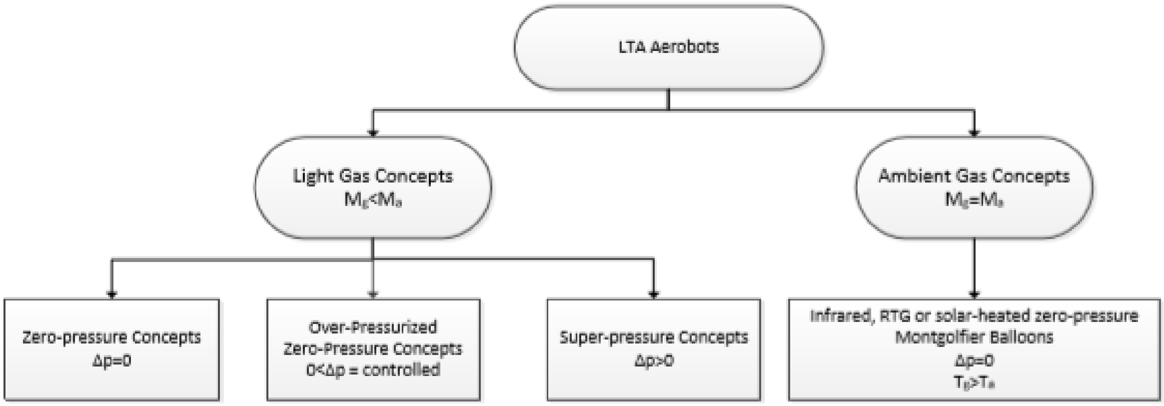

Figure 4.2: Types of Balloons, also known as LTA, lighter than air, aerobots

As shown in Figure 4.2, there are two main groups of balloons, dependent on the gas used inside the balloon envelope. The first group, which uses a low density gas, can be split into three types depending on the pressure difference between the dense gas and the surrounding atmosphere. For these concepts, the gas temperature is equal to the surrounding temperature. The second group uses the atmospheric gas. With this method, the temperature inside the balloon is an important factor with numerous methods to heat the gas mentioned in the figure. Each of the heating sources has its benefits and drawbacks, such as the 2000 Watt RTG heater providing a constant heating source for a Titan mission [19]. This is only made possible due to the dense atmosphere which allows for a larger lift force to be created due to a larger possible difference in density between the atmosphere and gas inside the balloon. This is shown in Equation 4.1.

To decide between the four concepts, a design option tree was created with the goal of being as complete as possible. However, the first three concepts, that achieve flight by using a low density gas, are already at a disadvantage due to possible out gassing that can occur. This will result in the gas slowly escaping the balloon and will need replenishing in time. This will ensure that the mission requires additional gas and is not sustainable. Furthermore, these balloons will be hard to store as the gas generally will not be pumped out of the balloon. Therefore, alternatives in the ambient gas branch were explored and are shown in Figure 4.3.

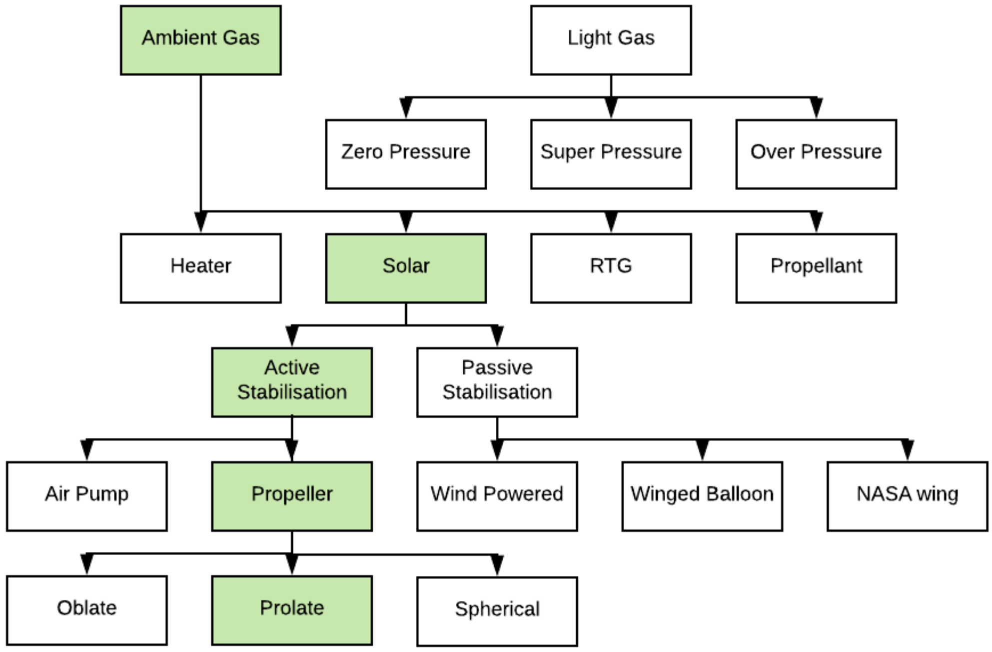

Figure 4.3: Design Option Tree

The first row of options, after the ambient gas balloon is chosen, relates to the gas heating options shown in Figure 4.2. These are separated in the electrical heater category, the use of an RTG or via solar energy. A widely used method is the burning of propellant to heat the insides of the balloon, similar to hot air balloons on Earth. Out of all options, the solar option is chosen as the most optimal option due to the requirement of using a renewable energy source.

The next step is deciding if stabilisation and control is wanted for the flying vehicle. The Passive Stabilisation path offers three methods to control the balloon. For example a deployed 'wing' far below the balloon to make use of the difference in wind speeds at different altitudes. An example is shown in [1]. Furthermore, a winged balloon could provide a certain amount of control, similar to a plane's wings while the wind powered option considers the balloon having a controllable tail which would act similar to a boat's sail. Whilst the third and final option is to change the shape of the balloon to take advantage of a variance in wind speed. For this thesis, a certain degree of control is a requirement, hence the choice to go down the active stabilisation path. Options here include an air pump to provide thrust, or the conventional propeller system. Since the balloon would be required to rotate both directions, two electric propellers system can do this by changing the rotation of the blades. This would be more difficult to achieve with an air pump or two.

5 Climate Conditions

In order to provide a preliminary design of the balloon for astronauts to use, a landing site is needed which will allow assumptions on the atmospheric conditions to be made.

Firstly, the needs of future colonists will be collected from multiple reports and summarised, after which a program is discussed which focuses on determining suitable settlement sites for astronauts based on a set of constraints. The final section will describe a selected landing site and the atmospheric conditions that are expected there.

5.1. Mars Colonist

This section describes the needs that are expected for future astronauts on Mars.

5.1.1. Supplies

The astronauts tasked with surviving on the Martian surface will need supplies. After a set amount of time, the supplies brought from Earth will run out. A supply chain between Earth and Mars is in the realms of possibility but given that the flight time between planets is long and expensive, it can be assumed that the supply drops will not happen often so this would be an inefficient solution. The need to be self sufficient on Mars is commonly discussed as an important aspect. This would, technically, allow Martian colonists to provide themselves with water, food and optimally even oxygen. On Mars, water is currently is in the form of ice under the surface [27]. The extraction process might be difficult but choosing a location that allows for this possibility is an aspect that is considered in this chapter.

Unfortunately for the astronauts, Mars does not grow its own vegetation and therefore the food aspect of being self sufficient will most likely not affect a desired settlement location. There are methods, however, that can sustain astronauts with food. An example is growing cyanobacteria on Mars and using it as a food and oxygen source, but there is no mention of a positional advantage [35].

To briefly summarise the criteria so far, three aspects are discussed that play a role in determining suitable settlement locations, which are the need for a water, oxygen and food source.

5.1.2. Atmosphere

An important aspect for future astronauts is the generation of power. On Mars, solar energy is as a good source of renewable energy that is available daily. To ensure that astronauts have enough solar energy to work with, a settlement location is needed that is closer to the equator. The requirement for solar flux directly influences the latitude range of the Martian surface that would be suitable, which will be shown in Figure 5.1. Solar flux is one of the main requirements for a settlement location because it is also beneficial for heating the balloon's gas and generate more lift.

A lower surface altitude or the Mars Orbiter Laser Altimeter elevation, MOLA, elevation is also beneficial for the lift generation of the balloon. This results in a higher density value in the atmosphere so that the difference between the atmospheric and balloon density is larger, resulting in more lift generation. More detailed calculations are shown in Chapter 6.

5.1.3. Extra Considerations

As discussed in the two previous sections, the astronauts are able to be self sustainable, given proper preparation, and can power their activities. However, this does not make the mission a simple task as there are other variables that need to be considered. First, radiation protection is one of the major obstacles regarding human health during space missions. There are reports dedicated to thinking outside the box and finding solutions to reduce the amount of radiation absorbed by the humans expected to travel to Mars. For example, one of the simplest solution is to use available landscape on Mars such as caves and tunnels, similar to what human's prehistoric ancestors have done [6]. Whilst this option would make life easier for future astronauts, it is difficult to depict where these cave and tunnels exist, especially in a numerical simulation. Therefore, this solution is not a guarantee.

The second aspect that needs consideration is the wind speed that is expected across the Martian surface. Not only will an area with strong winds be potentially dangerous for the astronauts and their equipment, it will also ensure that the balloon remains is. Therefore,a maximum wind speed must be determined to protect both the astronauts and the balloon.

The two remaining aspects vary greatly with location. These are the dust and surface conditions. Dust is harmful to solar cells, astronaut's spacesuits and spaceships on Mars and therefore, ensuring minimal dust in the surrounding area is key for sustainability throughout the mission [23]. The surface conditions, which includes the slope and roughness factors, do not impact the balloon but, can impact the lives of the astronauts on the surface. A flat and rock-less surface is the best situation for a small Martian base and this is what will be sought after.

5.2. ESS Program

Expert System: Settlement, ESS, is a program created by M. Noeker [27]. The thesis focused on creating a program that uses available data from the MCD to determine a human settlement location given a set of constraints. These constraints include 3 main types of limitations to the settle location. First, the climate conditions are entered. Main components of the atmosphere are required to do this, such as a minimum and maximum solar flux requirement. Constraints, named engineering constraints, are needed. These look into surface conditions such as slope, rock abundance and elevation. The set of constraints that are perhaps the most important for a settlement are called the resources constraints. Here, the user can input requirements for different resources, such as ice and basalt, to determine a location that fits to the mission. This program provides two main set of constraints that apply to this thesis. The climate and resource requirements are the most important due to the need of water and climate conditions that are fit for balloon flight.

The program is extensive and looks into each point of interest with detail by determining if a landing can happen by calculating a landing ellipse. All of the variables and constraints can be manually added and or changed to meet the desired goal. Fortunately, an example use of the ESS is given in the report and correlates with the needs discussed in this Chapter. The following values found in Table 3.12 found in [27] are used as requirements for this thesis.

- MFD-E1: Latitude shall be between 50' North and 50' South
- MFD-E2: Elevation shall be below 2 km MOLA
- MFD-E3: Site shall have less than 8% rock abundance
- MFD-E4: Average steady wind speed shall be less than 15 $\frac{m}{s}$
- MFD-E5: Maximum peak winds shall be less than 30 $\frac{m}{s}$
- MFD-E6: Site shall have a minimum of 5% weight percentage of water concentration

Using these constraints, the report provides Figure 5.1. The black markings in Figure 5.1 dictate the possible settlement sites that fit the constraints listed above. The only difference between all of the black markings is the elevation. To finalise the settlement site, the location of 3' North and 140' East is chosen as this is shown to be the lowest elevation described by the colour pattern in Figure 5.1, where blue represents a lower elevation.

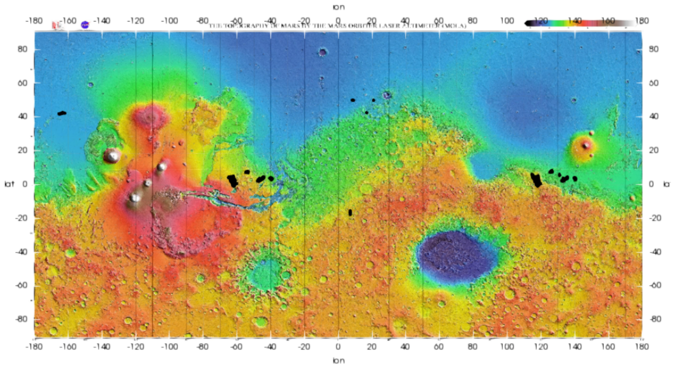

Figure 5.1: ESS example; Martian surface with possible settlement sites depicted by a black point

5.3. Selected Conditions

Figure 5.2 describes the conditions at the location 3' North and 140' East throughout the entire Martian year, at an elevation of 200 meters. The points on the graph are plotted for each day at the 12th Martian hour. The bottom axis plots the solar longitude. Figure 5.2 shows that the conditions vary greatly throughout the year, distinguishing different seasons. To design the balloon, atmospheric conditions need to be chosen. In order to allow the balloon to fly most often, the worst case scenario is chosen. The worst case scenario is considered to be the situation with the highest temperature out of all the points in Figure 5.2. This is found at a solar longitude of 195'. The conditions in this scenario are given in Table 5.1 which shows that at 195' solar longitude, the solar flux is at a yearly high of 574.8. Even though this would increase the gas temperature, this will also cause the atmospheric temperature to increase. This results in a reduction in density difference. More is shown in Chapter 6.

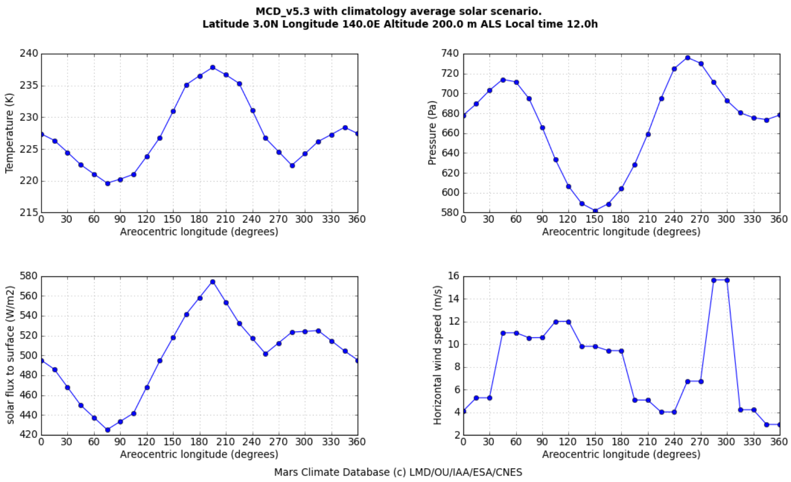

Figure 5.2: Graphs describing selected conditions throughout an entire year

Table 5.1: Worst Case Values at 200 meters above the chosen settlement location, representing a solar longitude of 195' at 12:00 Martian time

Variable	Value
Pressure (Pa)	628.5
Temperature (K)	237.8
Solar Flux (W/m^2)	574.8

6

Preliminary Design

The previous chapter discussed settlement requirements and provided a settlement site for this mission, with 5' North and 140' East being the chosen coordinates. The average atmospheric conditions are also discussed in Chapter 5. With these conditions determined, it is possible to provide a preliminary design. This chapter discusses the design and the methods used to calculate all aspects. This chapter also describes the results of simulating the altitude of the balloon over time.

6.1. Design Aspects

The preliminary design is a balloon with a prolate ellipsoid shape. A prolate has one axis, the major axis, longer than the other two which are equal in length. The ratio used in this design is determined to be 0.41, so that the longer radius is a factor of 2.44 longer than the short radius. See Figure 6.2. Other values of the design are shown in Table 6.1. These are found and calculated via the Equations described throughout this chapter using the assumptions given in Table 6.2. This design is possible using the assumptions found in Table 6.2. Furthermore, upon arrival, a pump is to be used by the astronauts. An example pump is given in Section 6.5.3 which results in the balloon being filled in a total of 9 hours and 51 minutes, requiring 30.5 kWh.

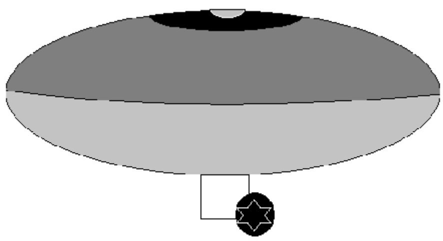

Figure 6.1: Example figure representing the balloon with all design aspects

Figure 6.1 describes various areas of the balloon with colour coding. The two main areas depicting both halves of the prolate ellipsoid indicate the coating used. The top is coated by Germanium whilst the bottom is coated by aluminium to ensure that the thermal properties of $\alpha = 0.6$ and $\epsilon = 0.03$ are possible.
Furthermore, the black area at the top of the balloon represents the solar cell area required to power the propellers. This area also contains a smaller area depicted by a grey colour. This represents the venting system.
Attached to the bottom of the balloon is the payload. The payload is connected to the bottom together with the two propellers which are depicted by the square box and black star, respectively.

Table 6.1: Preliminary design parameters

Variable	Value	Units
Volume	27184.1	$m3$
Long Axis Radius	33.80	m
Short Axis Radius	13.86	m
Balloon Mass	81.08	kg
Gas Temperature	456.69	K
Thrust	471.6	N
Solar Area	131.58	m^2
Vent Area	19.03	m^2

Table 6.2: Final assumptions used for the preliminary design

Variable	Value	Units
Payload	100	kg
Atmospheric Pressure	628.5	Pa
Atmospheric Temperature	237.8	K
Solar Flux	574.8	w/m^2
Gravitational Acceleration	3.71	m/s^2
Atmospheric Molar Mass	0.044	kg/mol
Envelope Surface Density	13	g/m^2
Maximum Wind Speed	15	m/s

6.2. Lift Force

This section describes the methods used to determine the size of the balloon. The initial process makes use of Archimede's law of buoyancy and the law of thermal equilibrium. This can be compared to both [14] and the thesis BADS [34].

6.2.1. BADS

BADS, Balloon Aerobot Design and Simulation, is a program created by a former Master student at the TU Delft, I. van Dosselaer. The thesis work summarises all main aspects of balloon design and provides software to design a balloon following requirements and constraints imposed on the system. All of this is programmed in MatLab and provides many options for balloons in multiple atmospheres, including Earth and Mars. Access to the software was granted and time was spent investigating what the software can offer this thesis work. The program offers a valuable design tool for most types of balloons.

However, the code can not be used to design a hot air balloon but for example, a super pressured balloon. It was decided that focus could be better spent using the main balloon equations which will be described in the next section.

Fortunately, the BADS report [34] has given a large amount of insight into balloons and the physics behind them and has helped immensely with this chapter. Furthermore, the MatLab program contains certain models, such as a more complicated thermal model than the model used in this thesis, which can benefit the accuracy of the simulation. This is further discussed in Chapter 7.

6.2.2. Designing

The physics for the lift are simple when compared to the complicated aerodynamics of airplane and flapping wing flight. This is due to the main force being provided by Archimedes's law of buoyancy which states that the upwards force is equal to the weight of the displaced fluid. This is described by Equation 4.1.

Equation 4.1 shows that the net lift produced is a function of the gas densities between the atmosphere and balloon. This provides the amount of lift that the balloon can generate but does not take into account masses other than the mass of the gas inside the balloon. In reality, the mass of the envelope, payload and further instruments would need to be included as well. Equation 6.1 describes the total mass expected for the balloon.

$$m_{total} = m_{payload} + m_{envelope} + m_{extras} \tag{6.1}$$

where: m_{total} = Total mass of the balloon (kg)
$m_{payload}$ = Mass of the payload (kg)
$m_{envelope}$ = Mass of the envelope and coating (kg)
m_{extras} = Mass of extras added onto the design, such as potential control mechanisms (kg)

The mass of the envelope is given by Equation 6.2.

$$m_{envelope} = A_{surface}\rho_{A_{material}} \tag{6.2}$$

where: $A_{surface}$ = Total surface area (m^2)
$\rho_{A_{material}}$ = Material surface density ($\frac{kg}{m^2}$)

Furthermore, the Ideal Gas law is needed as this relates the density to the pressure and temperature conditions of the atmosphere. This was shown in Equation 2.1 in chapter 2. The Ideal Gas law equation in Equation 2.1 explains why a hot air balloon is capable of providing lift, because a higher temperature results in a lower density gas. To meet the requirement of using a renewable energy source, as given in MFD-SH-5, the sun will act as the main power source for thermal heating.

To calculate the temperature of the gas, thermal equilibrium is assumed. Thermal equilibrium is the steady temperature of objects when the thermal input and output are equal. A further assumption made throughout these calculations is that the sun is at such a distance that the rays fall perpendicular to the top of the balloon. This ensures that only the top area of the balloon is heated. This is shown in Equations 6.3 to 6.5.

$$P_{in} = P_{out} \tag{6.3}$$

$$P_{in} = \alpha(A_{top} - A_{solar})S \tag{6.4}$$

$$P_{out} = \sigma\epsilon(A_{surface} - A_{solar})T_g^4 + h(A_{surface} - A_{solar})(T_g - T_{atm}) \tag{6.5}$$

where: P_{in} = Power gained by the balloon (W)
P_{out} = Power loss by the balloon (W)
α = Absorptivity coefficient, ranges from 0.0 to 1.0 ($-$)
A_{top} = Cross sectional area of balloon seen from above (m^2)
A_{solar} = Solar cell area (m^2)
S = Solar Flux ($\frac{W}{m^2}$)
σ = Stefan-Boltzmann constant, $5 * 10^{-}8$ ($\frac{W}{m^2K^4}$)
ϵ = Emmissivity coefficient, ranges from 0.0 to 1.0 ($-$)
$A_{surface}$ = Total surface area of the balloon (m^2)
h = Heat transfer coefficient, assumed to be 0.125 ($\frac{W}{m^2K}$)
T_g = Balloon temperature (K)
T_{atm} = Atmospheric temperature (K)

In Equation 6.5, the first term on the right hand side depicts the radiation heat transfer whilst the second term describes the convective heat transfer. Furthermore, the term A_{solar} mentioned here refers to the area taken up by solar cells. Section 6.5.2 discussed how to calculate the solar area. The absorptivity and emmisivity are both a function of the material and coating chosen for the balloon. Because the lift of the hot air balloon depends greatly on the internal gas temperature, both α and ϵ are critical design components.

The heat transfer coefficient is assumed to be equal to 0.125. In the NASA solar Mars balloon, no equations are provided for determining the gas temperature in the balloon. However, a value of 415 K is provided. Using Equations 6.3 to 6.5 with the size of the balloon, envelope and coating values provided in [14], a value of 415 K is found when the heat transfer coefficient is equal to 0.125. This is only true if the assumption that the NASA engineers used the same thermal equilibrium principle is correct. Another source assumes that the heat transfer coefficient for aluminized Kapton to be around

0.2 [13]. Whilst Kapton is not the same material used for this balloon, it does show that the value of 0.125 calculated above is similar and not an entirely wrong assumption to use throughout this report.

Equation 6.5 cannot be rearranged to find the gas temperature as it includes two forms of the variable, to the power of one and four. Therefore, to find the equilibrium gas temperature, Equation 6.3 must be reiterated until convergence.

With the gas temperature described, all remaining variables and therefore the lift, can be calculated. However, to design the balloon size, it will be assumed that the required lift needed is equal to the total weight of the balloon. This results in the following equation as derived from Equation 4.1.

$$V_{required} = \frac{W_{total}}{g_{mars} * (\rho_{atm} - \rho_{gas})} \tag{6.6}$$

where: $V_{required}$ = Required volume to provide lift equal to the weight of the balloon (m^3)
W_{total} = Total weight defined in Equation 6.1 (N)
g_{Mars} = Gravitational acceleration on Mars, 3.71 (m/s^2)
ρ_{atm} = Atmospheric density (kg/m^3)
ρ_{gas} = Balloon gas density (kg/m^3)

6.3. Shape Analysis

The shape of the balloon has not yet been discussed and whilst the material section uses an example with a spherical object, a spherical balloon may not be the chosen shape. This section will investigate an ellipsoid. There are two types of ellipsoids, as shown in Figure 6.2. The left object is an oblate ellipsoid whilst the right object is an example of a prolate ellipsoid.

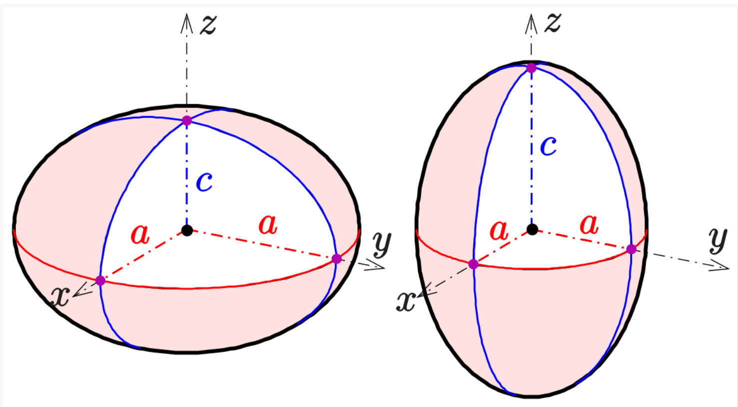

Figure 6.2: Ellipsoid shapes [28]

From Figure 6.2, it is seen that there are three main variables that are affected. These are the frontal, top and total surface area when compared to a sphere. The frontal area is the cross sectional area of the ellipsoid as seen from the front. These can be calculated with Equations 6.7 to 6.10.

$$A_{top} = \pi ac \tag{6.7}$$

$$A_{frontal} = \pi aa \tag{6.8}$$

$$ecc = \sqrt{1 - (\frac{a^2}{c^2})} \tag{6.9}$$

$$A_{surface} = (2\pi c^2) * (1 + (\frac{a}{c * ecc}) * asin(ecc)) \tag{6.10}$$

where: a = Radius of the short side (m)
c = Radius of the long side (m)

The effect of the ellipsoid ratio, which is the ratio of the short to long radius, on these three areas are discussed as these areas impact important parameters in the design. Firstly, the frontal area plays a role in the drag calculations whilst the balloon moves forward, or during a head on wind gust. The top and total surface area play a key role in the gas temperature as shown in Equations 6.4 and 6.5. Furthermore, decreasing the ratio to increase the length difference between the long and short axis will increase the total surface area. To this end, the prolate ellipsoid is added into the simulation and plotted for various ellipsoid ratios to determine the optimal shape. The prolate is chosen as this would decrease the frontal area and increase the top area which is beneficial. The oblate will do the opposite, reducing the efficiency of the balloon by providing a higher drag and less area to absorb sunlight.

The effect of changing the sphere into an increasingly more prolated shape is plotted and shown in Figure 6.3. Here, the variable on the X-axis is the ratio between the short axis and long axis, while the total weight is plotted on the Y-axis. Figure 6.3 shows that the ratio of 0.41 provides a lighter balloon. This graph is made possible due to the relationship between the top area and total weight. To plot this graph, the variables given in Table 6.2 are used to ensure that this ratio complies with the preliminary design. In this relationship, a larger top area results in more sunlight being absorbed and therefore, a higher temperature equilibrium. The volume inside the balloon, and the amount of envelope material needed also increases, but it can be deducted from Figure 6.3 that these do not grow at the same rates, meaning that a minimum occurs at 0.41. Therefore, the longer radius is a factor of 2.44 longer than the short radius.

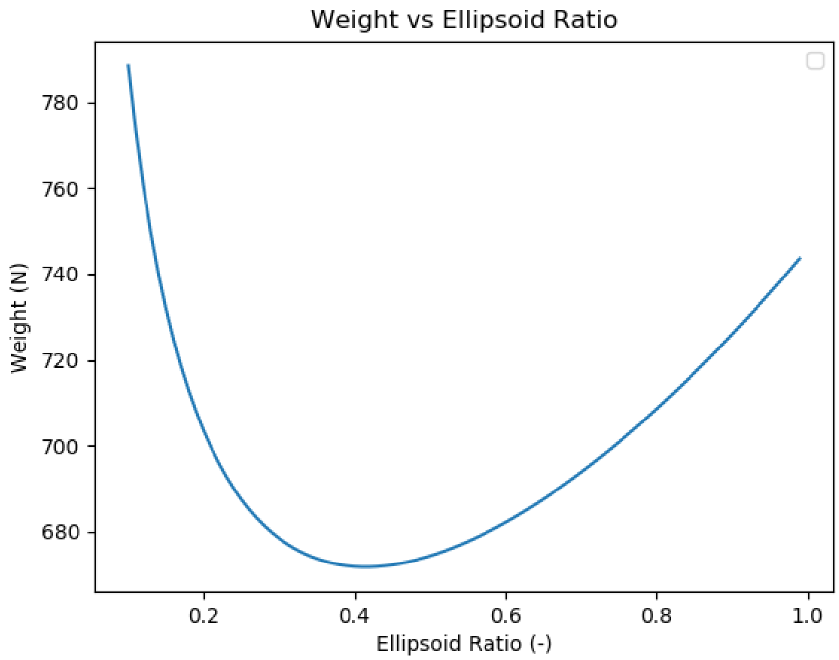

Figure 6.3: Weight vs Ellipsoid Ratio

With this in mind, the values for both radii can be calculated. This is done with Equation 6.11.

$$c = \left(\frac{V_{required}}{\frac{4}{3}\pi S_{ratio}}\right)^{\frac{1}{3}} \tag{6.11}$$

where: c = Radius of the long side (m)
$V_{required}$ = Required volume to provide lift equal to the weight of the balloon (m^3)
S_{ratio} = Prolate shape ratio, a ratio of minor divided by major axis ($-$)

6.4. Material Choice

The previous sections mention the importance of the absorptivity and emmisivity regarding the gas temperature inside the balloon. To this extent, this section discusses the chosen envelope material and various coatings.

One envelope material is commonly cited in Mars balloon research. This is a 3.5 μm thick Mylar fabric with a Kevlar mesh mentioned in [14]. The surface density of this combination of materials, mainly due to the thickness, is merely 9 to 13 $\frac{g}{m^2}$. This is relatively low, especially compared to other reports mentioning fabrics, such as the Titan mission [19]. The titan report mentions values of 47 and 75 g/m^2 for PVF - 'Tedlar' film and 20-micron polyester film, respectively. Due to this, [19] mentions that 100 g/m^2 is a good assumption when regarding strong polymer based envelopes. However, these materials are designed to perform bearing strong loads due to large pressures inside the balloon.

To confirm whether or not the material found in [14] is the best candidate, envelope materials were discussed at the TU Delft with the lead researcher in composites and polymers, Dr. J.C. Bijleveld. Here, it was mentioned that the Kevlar-Mylar mesh seems like a reasonable choice for a space mission and that lighter materials are unlikely to be found. Therefore, it is reasonable to assume that using the Kevlar-Mylar mesh is the best option for a Mars balloon envelope. To finalise the choice, the 13 g/m^2 value is used to provide a light balloon but also consider the weight of the coating.

Another factor that must be incorporated with the balloon's envelope is the type of coating used. In [14], the coating used is a germanium - aluminium coat. It would be easy to assume the same coating, especially due to its thermal properties of $\alpha = 0.6$ and $\epsilon = 0.03$.
A publication from NASA describes the space thermal properties of many different material and coatings [12]. Using this publication, it is possible to compare some of best coatings possible. The best coating for this balloon is one with a high absorptivity and low emmisivity as this will ensure that the balloon retains most of its heat.

Table 6.3: Coating properties

Design	α	$\epsilon_{combined}$
Blue anodized titanium foil	0.7	0.13
Tarnished copper foil tape	0.55	0.04
Tantalum foil	0.4	0.05
Polished tungsten	0.44	0.03
Vapor deposit: aluminum	0.08	0.02
Vapor deposit: germanium	0.52	0.09
Vapor deposit: nickel	0.38	0.04
GSFC SiO-Cr-Al dark mirror coating	0.86	0.04

It is assumed that the top area is directly influenced by sunlight and benefits from a higher absorptivity. The bottom half, however, does not require an absorptivity coefficient which allows the use of an extremely low emissivity material. This is only possible due to the assumption that only the top area is affected by solar energy. By using two materials, the combined emissivity value can be calculated with Equation 6.12.

$$\epsilon_{combined} = \frac{A_{top}\epsilon_{top} + A_{bottom}\epsilon_{bottom}}{A_{total}} \tag{6.12}$$

where: $\epsilon_{combined}$ = Average emissivity due to various coatings (-)
A_{top} = Top area (m^2)
ϵ_{top} = Emissivity applied on the top area (-)
A_{bottom} = Bottom area (m^2)
ϵ_{bottom} = Emissivity applied on the bottom area (-)

In order to calculate the combined emissivity, it is assumed that the bottom half is covered with aluminium. Aluminium is chosen as as it has a low emissivity coefficient of 0.08. For the absorptivity, there

is no combined value since only the top half is in direct sunlight and will absorb sunlight. Furthermore, Equation 6.12. describes the method to calculate the combined emissivity in which the top and bottom area are half of the total area.
Table 6.4 shows the combined thermal properties of four combinations: tarnished copper, polished tungsten, germanium and blue anodized titanium. These will be applied to the top area while aluminium will cover the bottom half. These coatings are selected as they provide a high absorptivity to emissivity ratio. A higher ratio is more beneficial for the balloon.

Table 6.4: List of chosen coatings and their respective effect on the gas temperature

Coating	α	$\epsilon_{combined}$	**Gas Temperature (K)**
Blue anodized titanium	0.7	0.075	397.25
Germanium	0.6	0.03	456.69
Polished tungsten	0.44	0.025	433.89
Tarnished copper	0.55	0.03	446.00

Lastly, to be able to compare these options with the germanium-aluminium coating [14], the gas temperature is calculated for a five meter spherical object covered in these coatings. It is assumed that the solar flux is 574.8 W/m^2 and an atmospheric temperature of 237.8 K.

According to the gas temperatures in Table 6.4, the germanium-aluminium still provides the higher gas temperature. This is the case even though the polished tungsten is the coating with the lowest combined emissivity which is caused by the absorptivity of the tungsten being lower than the germanium combination, their values being 0.44 and 0.6, respectively. Therefore, for the design, the germanium-aluminium coating from [14] is used.

6.5. Power

The design option tree in Chapter 4 states that the main control mechanism for the position will be a set of electric propellers. These propellers must be able to propel the balloon forward, backwards and be able to turn the balloon as well. To do this, it is envisioned that there will be two propellers, one of each side of the base.

6.5.1. Drag

As mentioned in the mission requirements, Chapter 3, the balloon must be able to counter, or stay stable, with a head wind of 15 $\frac{m}{s}$ as this is the maximum average wind speed in the settlement. To achieve this, the total thrust must be equal to the largest drag force that the mission is expected to experience. For this calculation, it is assumed that the wind is coming head on and that the thrust will face directly into the wind. With this, the total drag can be defined as Equation 6.13.

$$D = \frac{1}{2} C_D \rho_{atm} A_{frontal} Ve_{wind}^2 \tag{6.13}$$

where: D = Drag force from the wind acting on the balloon (N)
C_D = Drag coefficient, equal to 0.5 due to the spherical balloon (-)
$A_{frontal}$ = Cross sectional area as seen from the front of the balloon (m^2)
ρ_{atm} = Atmospheric gas density ($\frac{kg}{m^3}$)
Ve_{wind} = Wind velocity ($\frac{m}{s}$)

In order to determine the power requirement to counter the wind force, Equation 6.14 can be used [34]. This equation provides the amount of thrust needed to counter the maximum expected wind force at the settlement site.

$$P_{thrust} = \frac{Th * V}{\eta_{efficiency}} \tag{6.14}$$

where: P_{thrust} = Thrust power required (W)
Th = Thrust which is equal to the drag force (N)
$\eta_{efficiency}$ = Efficiency factor for the propeller system (-)

6.5.2. Solar Cells

The next step is to determine the power requirement to enable usage of all aspects of the balloon. These main balloon aspects are listed below:

- Sensors
- Thrust
- Vent
- Payload

Since the balloon will complement the astronauts on the surface, it does not need to power itself the entire day. It can also be assumed that the astronauts will only use the balloon if the atmospheric conditions allow. For example, the balloon will not be used during major dust storms, in the morning or in the evening due to lack of sunlight. The solar cells that are used must generate enough power to satisfy the power requirements. To achieve this, there are two possibilities. solar panels can either be placed above the balloon, or flexible solar panels can be attached to the envelope itself, as described in [13].

Report [13] was the winner of NASA's Big Idea competition in 2018. The report describes a mission to provide a solar energy gathering balloon and as such, provides a balloon covered with solar cells. The solar cells used in this report are gallium arsenide cells. These have the capability of bending, allowing for easier integration, especially on a curved surface such as the envelope. Therefore, the solar cells can be attached to the balloon directly as these can bend to a minimum of 5 cm of radius curvature.
An alternative method for gathering solar energy would be to use conventional solar panels and have them attached to the top of the balloon. This method is rigid and not capable of being placed along the balloons envelope. Between these options, it was decided that a flexible solar cell with the ability of being attached to the envelope is more suitable for this mission as it will allow for a more simple method of packaging. The solar cells have the following properties [13].

Table 6.5: Solar cell characteristics

Solar Cell Variable	**Value**	**Units**
Power Density	126	W/m^2
Cell Size	50 x 17.1	mm^2
Cell Weight	0.112	g

To determine the required solar cell area, Equations 6.15 can be used. The total power, P_{total} was calculated to be 11,053 W.

$$A_{solarcell} = 1.5 * \frac{P_{total}}{\rho_{power}} = 131.58m^2 \tag{6.15}$$

where: $A_{solarcell}$ = Solar Cell area required (m^2)
P_{total} = Total power, assumed to be equal to the thrust power requirement (W)
ρ_{power} = Power density of the solar cells ($\frac{W}{m^2}$)

The constant 1.5 found in Equation 6.15 is implemented to ensure that the balloon carries 50% extra solar panels. This adds a safety factor to the solar power generation as the solar cells will degrade over time. Furthermore, this helps ensure that dust does not end the balloons capability of generating power during dustier seasons.

According to [13], each solar cell weighs 0.112 g and has a size of 50 mm by 17.1 mm. The number of cells in a square meter, N_{cells}, is thus 1170. With the number of cells known, the overall density can be calculated which can then be used to determine the total weight of the solar panel area. Equation 6.16 shows the calculation for the surface density of the solar cells.

$$\rho_{solarcell} = N_{cells} * m_{cell} = 131 \frac{g}{m^2} \tag{6.16}$$

where: $\rho_{solarcell}$ = Surface density of solar cells ($\frac{g}{m^2}$)
N_{cells} = Number of cells per square meter ($-$)
m_{cell} = Mass of a single solar cell (g)

Therefore, the total weight of the solar cells is the solar cell area calculated in Equation 6.15 multiplied by the surface density in Equation 6.16.

6.5.3. Gas Pump

Before flight is possible, the balloon must be filled with the Martian gas after it has landed on the surface. Therefore, the balloon will be sent to Mars with an air pump that can be used by astronauts to pump air into the balloon. [13] provides an example of a pump able to do its job on Mars. For initial calculations, it is assumed that the current pump specifications are similar. The characteristics are provided in Table 6.6[13].

Table 6.6: Pump characteristics [13]

Variable	Value	Units
Mass	44	kg
Flow Rate	46	m^3/min
Size	45 x 0.8 x0.2	m^3
Power	3.1	kW

With the current specifications of the pump, it takes 9 hours and 51 minutes to fill the 27184 m^3 of the balloon. The power equivalence of this is 30.5 kWh. Therefore, emptying and storing the balloon should only be done when absolutely necessary, unless the waiting time and power requirements for pumping are not important.

6.5.4. Instrumentation

This section will describe some of the key instruments required to ensure the balloon is able to fly and adjust according to the conditions it finds itself in. This section will describe the main components required for flight control. The balloon is controlled by an astronaut but to control an object flying far away, the astronaut will need sensory feedback such as:

- Wind conditions
- Atmospheric conditions
- Balloon conditions

Wind conditions are important as these will greatly affect the balloon's position and velocity. To be able to continue its original direction, or remain in a location, the thrust will must be activated to counter the incoming wind. The two remaining aspects, the atmospheric and balloon conditions are the two greatest influences on the lift generation in balloons. This is where instrumentation such as sensors play a key role. Sensors record data and provide said data back to the astronaut as feedback of what is happening. By doing this, the astronaut can recognise whether additional movements are required to control. This is important because variables such as altitude and speed depend on constantly varying conditions. For the aspects listed above, the following instruments are needed.

- Camera
- Static pressure
- Dynamic pressure
- Temperature sensor

- Telecommunications

In flight, a pitot tube is used to measure the total pressure in a gas. A modified version of the pitot tube can also be used to measure the static pressure, P_s [26]. With these values measured, the dynamic pressure can be calculated using Equation 6.17 [32].

$$Pa_{total} = Pa_{static} + Pa_{dynamic} = Pa_{static} + 0.5\rho_{atm}V_e^2 \tag{6.17}$$

where: Pa_{total} = Total pressure of the wind stream, also known as stagnation pressure (Pa)
Pa_{static} = Static pressure of a wind stream (Pa)
$Pa_{dynamics}$ = Dynamic pressure of a wind stream (Pa)
ρ_{atm} = Atmospheric density ($\frac{kg}{m^3}$)
V_e = Flight speed ($\frac{m}{s}$)

From the dynamic pressure, the balloon's flight speed can be calculated. Other than a pitot tube for Mars, another important sensory need is a heat sensor used to determine the gas temperature inside the envelope. This could prove beneficial to calculate the current lift force. A camera is perhaps the most important out of all the required instruments listed above. Even though a pitot tube, or temperature sensor can accurately determine flight variables such as lift, a camera can be used to provide the operator an image of the current position, direction and a clear view of the surrounding area. Cameras are also able to provide a preliminary method of obstacle avoidance. Lastly, the balloon's computer shall have a telecommunication instrument to ensure that the astronaut can communicate with the balloon.

6.5.5. Radiation

Radiation is a dangerous aspect of Martian exploration and one that needs consideration. According to [11], there are two types of radiation that must be considered for a mission on Mars. These are the abbreviations GRC and SEP types, which are called galactic cosmic rays and solar energetic particles, respectively. Due to these constant sources of radiation, electronics in space have the tendency of being affected by power resets and system failures. These are caused by long exposures or even unpredictable solar activity [16]. NASA describes that there are currently three ways of protecting a spacecraft from radiation which are [16]:

- Passive shielding
- Redundancy
- Increasing radiation hardness of electronics

The passive shielding is also mentioned in [11], with coatings that have densities between 9 to 20 g/m^2. Fortunately, most of the vehicle is made of a light envelope containing Martian gas. There is no need to protect the Martian gas. The instrumentation, however, is located under the balloon and will therefore be protected by the large volume of gas above it. Furthermore, it will be assumed that the payloads provided by customers are protected from radiation. However, some of the sensors described in the previous section need to be exposed to the atmosphere. For any instrumentation that does require extra protection, the 'box' containing all electronic equipment can be coated against radiation by a material weighing up to 20 g/m^2, if necessary [8].

6.6. Simulation

This section will show the altitude vs time of the preliminary design. The methods and calculations used to simulate the expected flight path of a balloon on Mars are described here and are shown in full in the code [36].

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6.6.1. Simulating Each Second

The simulations used throughout this chapter are based on the equations used from the BADS Thesis [34]. A python script was created to model the hot air balloon designed for Mars. The first step towards this simulation is to understand that all aspects will be simulated every second, to ensure that the gas temperature and atmospheric conditions are constantly updated and are as accurate as possible. Then, the next step of simulating is to define the equations that are used in the program. A new variable is introduced, the virtual mass, which depicts the mass-spring behavior of the balloon which can be described as follows: "In a physical sense, this added mass is the weight added to a system due to the fact that an accelerating or decelerating body, in unsteady motion, must move some volume of surrounding fluid with it as it moves. The added mass force opposes the motion". This is described by Equation 6.18 [34].

$$m_{virtual} = m_{total} + C_{virtual}\rho_{gas}V_{balloon} \tag{6.18}$$

where: $m_{virtual}$ = Virtual mass (kg)
m_{total} = Total mass of the system (kg)
$C_{virtual}$ = Virtual mass coefficient, 0.35 (-)
ρ_{gas} = Balloon gas density ($\frac{kg}{m^3}$)
$V_{balloon}$ = Balloon volume (m^3)

By using this mass-spring behavior, the lift of the balloon can be calculated which is then used to depict the flight path of the balloon. The lift is calculated using Equation 4.1.

$$F_{Net} = F_{Lift} - D \tag{6.19}$$

where: F_{Net} = Net force generated (N)
F_{Lift} = Lift force via Equation 4.1 (N)
D = Drag force on the balloon via Equation 6.13 (N)

The drag force is present in Equation 6.19 because the balloon will undergo a movement in the simulations. It is assumed that C_D, the drag coefficient, has a value of 0.5 due to the prolated ellipsoid having a ratio that resembles a sphere closely. Once the net force is calculated, the acceleration is found via Newton's law of $F = ma$ which is related to the virtual mass as described in Equation 6.20.

$$\frac{dV}{dt} = \frac{F_{Net}}{m_{virtual}} \tag{6.20}$$

where: $\frac{dV}{dt}$ = Altitude acceleration ($\frac{m}{s^2}$)

The following two equations are used to determine the balloon's vertical flight speed and altitude, respectively.

$$V_{ascent_n} = V_{ascent_p} + \frac{dV}{dt} * dt = V_{ascent} + \frac{dV}{dt} \tag{6.21}$$

where: V_{ascent_n} = Newly calculated ascent speed ($\frac{m}{s}$)
V_{ascent_p} = Ascent speed from previous simulation loop ($\frac{m}{s}$)
$\frac{dV}{dt}$ = Altitude acceleration ($\frac{m}{s^2}$)
dt = Time differential (s)

$$H_n = H_p + V_{ascent} * dt = H + V_{ascent} \tag{6.22}$$

where: H_n = Newly calculated altitude (m)
H_p = Altitude from previous simulation loop (m)
V_{ascent} = Ascent speed ($\frac{m}{s}$)

So far, the equations for the speed of ascent is derived. However, as time goes by, more energy will be absorbed by the balloon and therefore the gas temperature will increase as a result which in turn affects the velocity. Then, as the altitude changes, so do the atmospheric conditions. These two aspects are updated at the end of each loop to ensure the following loop is performed correctly. The following section will discuss both variables in detail.

6.6.2. Variables

The gas temperature is a function of the power absorbed by the balloon minus the power emitted via radiation and convection. The following equation is similar to Equations 6.3 to 6.5 but the goal here is to calculate the net power in or out of the system, meaning that the input variables are different. Furthermore, thermal equilibrium is unlikely due to the constant changes in atmospheric conditions. The total power into the system is the difference between the power into and out of the system. At the start of the simulation, the gas temperature is equal to the local atmospheric temperature. From this, the total power which is used to heat the entire volume of gas inside the balloon is calculated. To find the change in temperature due to this power, Equation 6.23 is used.

$$\Delta T = \frac{P_{total}}{m_{gas} C_P} \tag{6.23}$$

where: P_{total} = Total power (W)
m_{gas} = Mass of balloon gas (kg)
C_P = Heat coefficient ($\frac{J}{K}$)

Furthermore, the atmospheric conditions of the selected Mars settlement site must be implemented into the program. To achieve this, the hourly changes in temperature and pressure are determined via the MCD. This provides values for a 24 hour period that can be used to simulate a day of operations for the balloon. Then, two assumptions are made. Firstly, it is assumed that at any point in time the values for the pressure and temperature can be found via Equation 6.24.

$$X = x_1 + \frac{x_2 - x_1}{3600} * t_s \tag{6.24}$$

where: X = Value at current time (-)
x_1 = Value at previous hour (-)
x_2 = Value at next hour (-)
t_s = Time since last hour mark in seconds (s)

This equation describes a linear increase of either the pressure or temperature values as time increases between the two hourly conditions. The second assumption is that the pressure and temperature vary with altitude corresponding with Equations 6.25 and 6.26 as given by NASA [25].

$$P_{atm} = P_0 e^{-0.00009*H} \tag{6.25}$$

$$T_{atm} = T_0 - 0.000998 * H \tag{6.26}$$

where: P_{atm} = Atmospheric pressure (Pa)
T_{atm} = Atmospheric temperature (K)
P_0 = Surface pressure (Pa)
T_0 = Surface temperature (K)
H = Balloon altitude (m)

6.7. Results

In order to get a clear picture of the expected flight path of the balloon, three scenarios are considered. These are the worst, average and best case scenario's in terms of atmospheric conditions. The balloon is designed with the worst case in mind, as described in Chapter 5. The daily atmospheric conditions for these scenarios are shown in Appendix 9. Using these varying conditions, the graphs are shown in Figure 6.4.

Figure 6.4 shows the flight paths for the three scenario chosen above. The worst case scenario shows that the balloon will achieve flight at around 8:30 Martian time and lands at 11:30. These are the conditions for which the balloon is designed for as these conditions provide minimum amount of flight time.The best case however, achieves lift-off at 7:30 Martian time and lands at 15:00 Martian time. For all three of the flight profiles, the balloon begins the simulation with the entire envelope filled and the

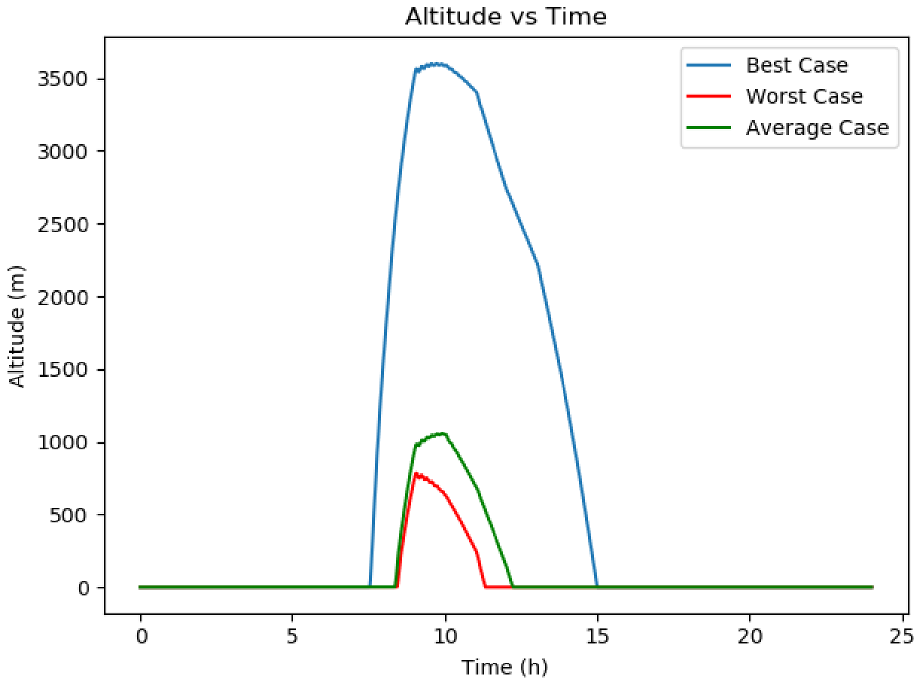

Figure 6.4: Altitude flight path simulation for the worst, average and best case scenario

balloon gas temperature is equal to the atmospheric temperature.

The first aspect that is noticed is that the three plots indicate that the atmospheric conditions greatly impact the flight capabilities of the balloon. This is mainly due to the varying pressure in the atmosphere. Whilst a low density is the target for the balloon gas, the atmospheric pressure affects both density values, due to the Ideal Gas law shown in Equation 2.1. A higher atmospheric pressure therefore leads to a higher density difference between the balloon gas and the atmosphere and therefore more lift capabilities. This is further enhanced by the fact that during the earlier times, such as between 08:00 and 10:00, the Martian environment has not reached its maximum temperature of the day. Furthermore, the graphs have high altitude peaks due to the altitude effect of Equations 6.25 and 6.26 further reducing the atmospheric conditions which makes the environment more beneficial for balloon flight.

Fortunately, a positive note from this unexpectedly high flight profiles is that the available flight time far exceeds the requirement MFD-CTL-5. This also occurs in the worst case scenario which represents the day with the highest temperature of the year. It is important to note that Figure 6.4 shows the flight path without human interference. However, control of the balloon, especially altitude control, is desired and is given in the requirements. To achieve this, two methods are possible.

Firstly, a vent at the top of the balloon can be used to allow the heated gas to escape. Secondly, changing the payload weight before flight will also affect the balloon's altitude throughout flight. These two control aspects are discussed in the following sections.

6.7.1. Venting

In order to design the vent size, one scenario is considered:

- The scenario in which the balloon must stay grounded the whole day.

Since the balloon will be used by astronauts, it is possible that the balloon will be stored, especially during dusty or stormy periods. However, pumping up or deflating the balloon is not instantaneous and to save energy, the astronauts might choose to keep the balloon filled but grounded. To keep the balloon grounded, the gas temperature must kept close to the atmospheric temperature to ensure that the balloon does not achieve a lifting force capable of carrying the balloon's weight. This can be achieved by looking at the situation in which the vent is opened continuously. In this case, the hot air is allowed to escape and the balloon will only be filled by colder, atmospheric gas and no lift force will be available.

After the balloon's gas escapes, more gas will enter from the opening under the balloon. Due to this, the gases will mix and the temperature of the heated gas will decrease due to the influence of the cold atmospheric gas. To calculate the new temperature of the the gases, Equation 6.27 can be used.

$$T_{new} = \frac{T_g m_{gas} C_{P_g} + T_{atm} m_{in} C_{P_{atm}}}{m_{gas} C_{P_g} + m_{in} C_{P_{atm}}} \tag{6.27}$$

where: T_{new} = Updated temperature (K)
T_g = Balloon gas temperature (K)
m_{gas} = Mass of the gas, shown in Equation 6.28 (kg)
C_{P_g} = Heat coefficient of balloon gas ($\frac{W}{m^2K}$)
T_{atm} = Atmospheric temperature (K)
m_{in} = Mass of the gas entering from below, shown in Equation 6.29 (kg)
$C_{P_{atm}}$ = Heat coefficient of atmospheric gas ($-$)

According to [33], the specific heats for carbon dioxide at temperature of 250 K and 400K are 791 and 939, respectively. The two masses in Equation 6.27 can be described by Equation 6.28 and 6.29.

$$m_{gas} = (V_{balloon} - V_{outflow})\rho_{gas} \tag{6.28}$$

$$m_{in} = V_{outflow}\rho_{atm}dt \tag{6.29}$$

where: $V_{balloon}$ = Balloon volume (m^3)
$V_{outflow}$ = Volumetric flow out of balloon via the vent ($\frac{m^3}{s}$)
ρ_{gas} = Balloon gas density ($\frac{kg}{m^3}$)
ρ_{atm} = Atmospheric density ($\frac{kg}{m^3}$)
dt = Time differential, in the simulation is equal to 1 second (s)

It is important to note that since each loop in the simulation represents one second, that the mixing of the gases is being simulated in an instant which, in reality, would not be the case. Furthermore, Equation 6.27 represents an ideal gas mixing process, and as such does not take any losses in consideration. In order to determine the required vent outflow, a continuous out flow is added into the simulation code. This simulates a vent that is always open. To determine the proper volumetric out flow required, the graphs in Figure 6.4 must not show any altitude change.
Through trial and error, it was found that 117 m^3/s is required to keep the balloon on the ground, even for the best case scenario where a higher lift force is expected due to the more favourable conditions. This result is found when simulating each of the cases until no altitude change is seen in the figures.

To represent the volumetric flow of 117 m^3/s into a vent area, the Bernoulli equation is needed. There will be a pressure difference across the top of the balloon and the atmosphere due to the temperature variations. This induces a flow speed through the vent as described by Equation 6.30 which is a reformulation of the Bernoulli Equation 6.17.

$$V_{e_{flow}}^2 = \frac{P_{atm} - P_{gas}}{\frac{1}{2}\rho_{gas}} \tag{6.30}$$

where: $V_{e_{flow}}$ = Flow velocity ($\frac{m}{s}$)
P_{atm} = Atmospheric pressure (Pa)
P_{gas} = Balloon gas pressure (Pa)
ρ_{gas} = Balloon gas density ($\frac{kg}{m^3}$)

The velocity can then be used with the mass flow equation to deduce the required vent area. The volumetric flow is equal to the mass flow divided by the density of the flow. Using this knowledge together with the flow velocity from Equation 6.30, the following can be derived:

$$A_{vent} = \frac{V_{flow}}{V_{e_{flow}}} = 19.03m^2 \tag{6.31}$$

where: A_{vent} = Vent area (m^2)
V_{flow} = Volumetric flow ($\frac{m^3}{s}$)

Now that the required vent area is determined to be 19.03 m^2, the effect of this vent is shown in Figure 6.5. The graph presented here is the controlled version of the worst case as described in Figure 6.4. Naturally, depending on the method of venting, the target altitude and the length of venting bursts will change the outcome of Figure 6.5. However, for the figure, it was decided to focus on the control altitude of 200 m. Once above this altitude, the vent will be opened for 8 s. The code then ensures that the vent stays closed for a minimum of ten seconds. This process leads to the simple control seen in Figure 6.5.

Figure 6.5 shows that it is possible to control the balloon with the venting system. The on board computer will need to be programmed to determine the best method of control. For example, when the balloon first reaches 200 m in Figure 6.5, the balloon does not need to vent for 8 s. Because this almost causes the balloon to land. This also applies around 10:00 Martian time where the vent requires a longer open period. The change in required venting times are caused due to the solar flux becoming stronger and therefore, the gas temperature in the balloon becoming higher. Therefore, when the solar flux is higher, more venting is needed to compensate for the gas receiving more energy from the sun.

However, determining the most optimal control mechanism is not the focus of this thesis.

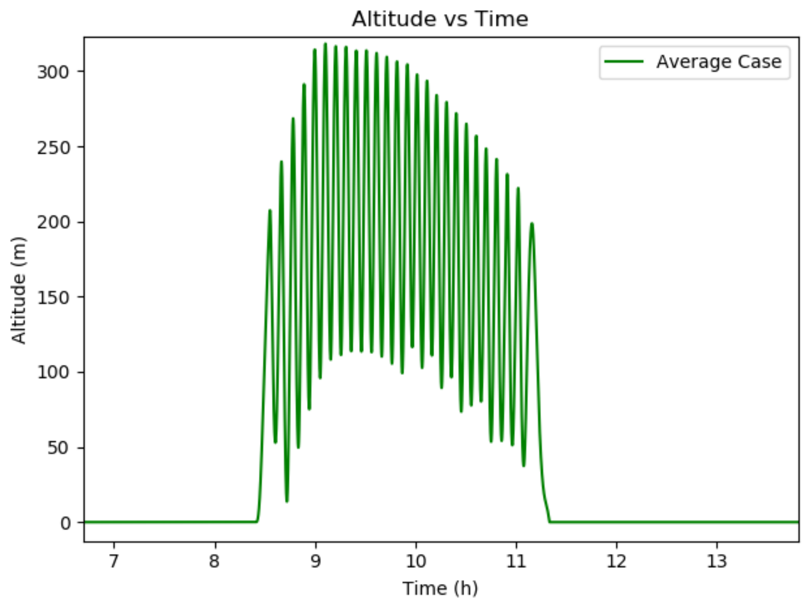

Figure 6.5: Example altitude control simulation of balloon with target altitude of 200 meters

6.7.2. Weight difference

A second option to control the altitude is by changing the payload weight before flight. This is a passive method as it would only control the maximum altitude and the amount of flight time possible. This is more beneficial in when the atmospheric conditions are not optimal for balloon flight as it increases the available lifting force by reducing the total weight of the balloon. An example of the effect of reducing the payload weight to 75 kg on the balloon flight during the worst conditions is shown in Figure 6.6. The astronauts are able to tailor the balloon flight to the mission by manually changing the payload carried.

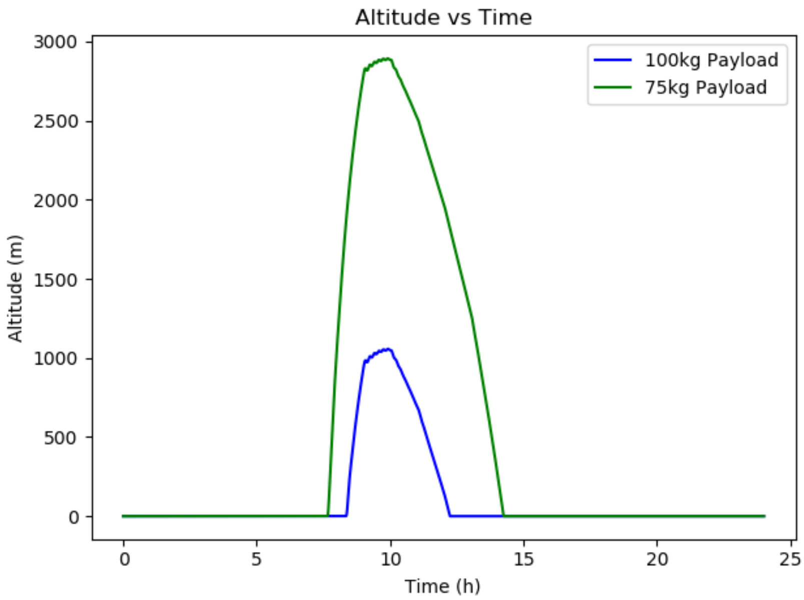

Figure 6.6: Effect of payload weight on maximum altitude

6.8. Verification and Validation

The topic of verification and validation, V&V, is important for scientific reports to ensure that the work presented can be replicated and is actually correct.

First, the most important part of the designing process is determining what size the balloon must be to lift a 100 kg payload. This is calculated with Equation 6.6 and 6.11. To verify whether this method works, the equations are used for the balloon example in [14]. In this report it is unclear how the size of the balloon was determined. Rather, a set of assumptions are given and the final result provided. These assumptions, which are shown in Table 6.7, are used and the result is shown in Table 6.8.

Table 6.7: Assumed variables used in [14]

Variable	Value	Units
Pressure (@ 3km)	457	Pa
Atmospheric temperature	200	K
Absorptivity	0.6	-
Emissivity	0.03	-
Solar Flux	500	W/m^2
Payload	10	kg
Envelope Density	9	g/m^2
Shape	Spherical	(-)

By using these assumptions into the program, it is possible to compare both methods of calculating balloon size. The balloon diameter given in [14] for the assumptions in Table 6.7 is 17.96 m. Furthermore, the balloon mass is 9.12 kg. Whereas, using the process described throughout this chapter and the code created to simulate these equations, the result for the balloon sizes are 18 m and 9.16 k. The comparison is shown in Table 6.8. Unfortunately, the simulation provided in [36] cannot be compared to any altitude simulations as these are not provided with enough information for a comparison.

Table 6.8: Design values for a 10kg payload using assumptions from Table 6.7

Variable	**Example**	**Code**	**Units**
Diameter	17.96	18.00	m
Balloon Mass	9.12	9.16	kg

Naturally, more verification is always better, especially with the simulation and code provided in [36]. However, no reports with information that can be used to verify these sections have been found. To this end, Chapter 7 discusses potential methods or experiments that can be done to provide the verification and validation of other aspects.

7
Future Work

This chapter will discuss a few key aspects of the thesis that can be expanded. This includes the use and incorporation of numerous software that is available and looking into improvements that can be made.

7.1. External Programs

One of the main supplements this thesis might benefit from is the incorporation of the MCD. The code in [36] uses initial values from the MCD to determine the pressure and temperature conditions at any time and altitude throughout one entire Martian day. Instead of manually entering all of the values if a different date is preferred, the MCD can be incorporated which will then simplify and reduce the time it takes to change the date. This will simplify the process of determining the flight characteristics of the balloon on different dates.

Not only would the incorporation of the MCD benefit this report, but the ESS program mentioned in Chapter 5 could as well. The ESS thesis provides available landing sites depending on detailed input criteria. This program also makes use of the MCD. Currently, the settlement site used throughout this report is chosen based on the results of an example given in the ESS report. The addition of the ESS code with the code in [36] would only a suitable choice if the user is in need of a specific, or more constrained, settlement site.

The last programming additions that would benefit this report are functions from the BADS thesis. The BADS program is written in MatLab and provides a tool to calculate the size, trajectory and other components of a balloon. It provides a similar, but more extensive, tool than the code provided based on Chapter 6.

7.2. Internal Program Changes

Further benefits to the code in [36] would consist of additional functions or details to calculations, such as the thrust, thermal model and perhaps even heat mechanics inside the balloon. The required thrust is calculated using 6.14 which is a validated equation. The thrust design components such as propeller width, length and pitch are not determined. Extra work following this thesis can focus on a more detailed thrust system and perhaps, even find a better alternative. The same applies to the thermal model used. In the BADS thesis, an extensive thermal model exists which accounts for conduction, convection and radiation. Equation 6.5 focuses on radiation and convection, which are the main sources of energy. This thermal model can be improved and this might impact the gas temperature. Changing the gas temperature will affect the altitude profile of the design.

7.3. Experiments

In addition to the numerical changes described above, experiments can also benefit this thesis work. The thermal calculations used throughout this thesis are relatively simplistic due to the assumptions of instantaneous and ideal heat exchange. Whilst the simple model is not incorrect, some inaccuracies might occur. To this end, providing a test in the Earth's atmosphere to check how the thermal model deviates to real life heat transmission could prove beneficial. This test might also be possible in a simulated Martian environment.

Furthermore, the propulsion system calculates the total drag and determines the required thrust to counter it. Whilst the calculations have been verified, determining the speed at which a balloon can control its position could be crucial for future Mars astronauts. Therefore, a possible test is one that tests the control of a large balloon, with a similar size as the preliminary design, by using a set of two propellers.

The final necessary aspect is verifying the work done in this report, which can be achieved with the use of experiments. When available, the validation of certain equations and codes are provided in Chapter 6. However, because little research is provided in predicting the flight path and characteristics, there are no sources to compare the results to. Therefore, the science community can benefit from a Martian environment balloon experiment.

8 Conclusions

This thesis discussed various flying vehicle concepts that can be used by astronauts to explore the Martian environment more easily. To establish whether such a vehicle is possible, a few key requirements were imposed on the design. These are the following:

- MFD-SH-5: Shall make use of a renewable energy source
- MFD-CTL-1: Shall have a mechanism to control altitude
- MFD-CTL-3: Shall be able to carry 100 kg
- MFD-E2: Elevation shall be below 2 km MOLA
- MFD-E6: Site shall have a minimum of 5% weight percentage of water concentration

The outcome of the trade-off that ensured the requirements were met. The conclusion of the trade-off is that a hot air balloon is the most power efficient flying vehicle. Not only this, but ballooning has the highest technology readiness level of the four concepts, which includes ornithopters, rotorcraft and aircraft. Another advantage that a balloon presents is the lowest amount of risk regarding mission failure and astronaut safety Before starting the design process, it was decided to determine a suitable settlement site for future astronauts. By using the ESS program, a final settlement site that fit all the imposed requirements was determined, located at 3' North and 140' East. This settlement site was used a the design location. The balloon is a hot air balloon with a prolate ellipsoid shape with a ratio of 0.41. This ratio is optimal to ensure minimal weight in the conditions at the settlement site, described in Chapter 5. Other final design variables of the design are shown in Table 8.1.

Table 8.1: Preliminary design variables

Variable	Value	Units
Volume	27184.1	m^3
Long Axis Radius	33.80	m
Short Axis Radius	13.86	m
Balloon Mass	81.08	kg
Gas Temperature	456.69	K
Thrust	471.6	N
Solar Area	131.58	m^2
Vent Area	19.03	m^2

To come to these results, the assumptions in Table 8.2 were used. The entire design process can be found in the previous chapters and in the code found in [36].

Table 8.2: Final assumptions used for the preliminary design

Variable	Value	Units
Payload	100	kg
Atmospheric Pressure	628.5	Pa
Atmospheric Temperature	237.8	K
Solar Flux	574.8	W/m^2
Gravitational Acceleration	3.71	m/s^2
Atmospheric Molar Mass	0.044	kg/mol
Envelope Surface Density	13	g/m^2
Maximum Wind Speed	15	m/s

To answer the questions surrounding Mars and its past, this thesis describes a hot air balloon on Mars that would be feasible design to help discover the answers to the biggest questions surrounding Mars. The balloon would provide the Martian astronauts with a method of gathering data, transporting goods or explore impassable terrain in an efficient manner.

Bibliography

[1] KM Aaron, KT Nock, MK Heun, and AA Pankine. A method for planetary balloon flight path guidance. In *4th International Planetary Probe Workshop, Pasadena, CA*, 2006.

[2] Andrew Ball, James Garry, Ralph Lorenz, and Viktor Kerzhanovich. *Planetary landers and entry probes*. Cambridge University Press, 2007.

[3] Yagiz Bayiz, Mohammad Ghanaatpishe, Hosam Fathy, and Bo Cheng. Hovering efficiency comparison of rotary and flapping flight for rigid rectangular wings via dimensionless multi-objective optimization. *Bioinspiration & biomimetics*, 13(4):046002, 2018.

[4] James E Bluman, Jeremy A Pohly, Madhu K Sridhar, Chang-kwon Kang, David Brian Landrum, Farbod Fahimi, and Hikaru Aono. Achieving bioinspired flapping wing hovering flight solutions on mars via wing scaling. *Bioinspiration & biomimetics*, 13(4):046010, 2018.

[5] Octave Chanute. *Progress in flying machines*. Courier Corporation, 1997.

[6] Glen E Cushing. Candidate cave entrances on mars. *Journal of Cave and Karst Studies*, 74(1): 33–47, 2012.

[7] GCHE De Croon, M Perçin, BDW Remes, R Ruijsink, and C De Wagter. *The DelFly*. Springer, 2016.

[8] Marco Durante. Space radiation protection: destination mars. *Life sciences in space research*, 1: 2–9, 2014.

[9] ESA. Why to go to mars. `https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Exploration/Why_go_to_Mars`.

[10] François Forget, Frédéric Hourdin, Richard Fournier, Christophe Hourdin, Olivier Talagrand, Matthew Collins, Stephen R Lewis, Peter L Read, and Jean-Paul Huot. Improved general circulation models of the martian atmosphere from the surface to above 80 km. *Journal of Geophysical Research: Planets*, 104(E10):24155–24175, 1999.

[11] Donald M Hassler, Cary Zeitlin, Robert F Wimmer-Schweingruber, Bent Ehresmann, Scot Rafkin, Jennifer L Eigenbrode, David E Brinza, Gerald Weigle, Stephan Böttcher, Eckart Böhm, et al. Mars' surface radiation environment measured with the mars science laboratory's curiosity rover. *science*, 343(6169):1244797, 2014.

[12] John H Henninger. Solar absorptance and thermal emittance of some common spacecraft thermal-control coatings. Technical report, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION WASHINGTON DC, 1984.

[13] Wade Hisiro, Matthew Julian, Elisa Pantoja, Arpan Sinha, George Wilkes, and Mool C Gupta. Photovoltaic balloon for autonomous energy generation on mars (mega-pb). 2018.

[14] Jack Jones and Jiunn Wu. Solar montgolfiere balloons for mars. In *International Balloon Technology Conference*, page 3852, 1999.

[15] Matěj Karásek, Florian T Muijres, Christophe De Wagter, Bart DW Remes, and Guido CHE de Croon. A tailless aerial robotic flapper reveals that flies use torque coupling in rapid banked turns. *Science*, 361(6407):1089–1094, 2018.

[16] Andrew S Keys, Michael D Watson, Donald O Frazier, James H Adams, Michael A Johnson, and Elizabeth A Kolawa. High-performance, radiation-hardened electronics for space environments. 2007.

[17] Geoffrey A Landis, Christopher LaMarre, and Anthony Colozza. Venus atmospheric exploration by solar aircraft. *Acta Astronautica*, 56(8):750–755, 2005.

[18] Jack J Lissauer and Imke De Pater. *Fundamental planetary science: physics, chemistry and habitability*. Cambridge University Press, 2013.

[19] Ralph D Lorenz. A review of balloon concepts for titan. *Journal of the British Interplanetary Society*, 61(1):2, 2008.

[20] Michael R Lynn. *The sublime invention: ballooning in Europe, 1783–1820*. Routledge, 2015.

[21] John C Mankins. Technology readiness levels. *White Paper, April*, 6:1995, 1995.

[22] John C Mankins. Technology readiness levels. *White Paper, April*, 6:1995, 1995.

[23] MK Mazumder, D Saini, AS Biris, PK Sriama, C Calle, and C Buhler. Mars dust: characterization of particle size and electrostatic charge distribution. 2004.

[24] Ehouarn Millour, Francois Forget, Aymeric Spiga, Margaux Vals, Vladimir Zakharov, Luca Montabone, Franck Lefèvre, Franck Montmessin, Jean-Yves Chaufray, Miguel López-Valverde, et al. The mars climate database (mcd version 5.3). In *Geophysical Research Abstracts*, volume 21, 2019.

[25] NASA. Mars' atmospheric model. `https://www.grc.nasa.gov/WWW/K-12/airplane/atmosmrm.html`, .

[26] NASA. Pitot tube. `https://www.grc.nasa.gov/www/k-12/VirtualAero/BottleRocket/airplane/pitot.html`, .

[27] Matthias Noeker. Ess: A settlement site selection tool for a human mars base. 2018.

[28] "Ag2gaeh" on Wikipedia. Wikipedia. `https://commons.wikimedia.org/wiki/File:Ellipsoid-rot-ax.svg`.

[29] Jeremy A Pohly, Chang-Kwon Kang, Madhu Sridhar, D Brian Landrum, Farbod Fahimi, James E Bluman, Hikaru Aono, and Hao Liu. Payload and power for dynamically similar flapping wing hovering flight on mars. In *2018 AIAA Atmospheric Flight Mechanics Conference*, page 0020, 2018.

[30] RZ Sagdeev, VM Linkin, JE Blamont, and RA Preston. The vega venus balloon experiment. *Science*, 231(4744):1407–1408, 1986.

[31] The Planetary Society. Missions to mars. `https://www.planetary.org/explore/space-topics/space-missions/missions-to-mars.html`.

[32] Oskar Karl Gustav Tietjens and Ludwig Prandtl. *Applied hydro-and aeromechanics: based on lectures of L. Prandtl*, volume 2. Courier Corporation, 1957.

[33] Engineering Toolbox. Carbon dioxide gas - specific heat. `https://www.engineeringtoolbox.com/carbon-dioxide-d_974.html`.

[34] I Van Dosselaer. Buoyant aerobot design and simulation study: Bads. 2014.

[35] Cyprien Verseux, Mickael Baqué, Kirsi Lehto, Jean-Pierre P de Vera, Lynn J Rothschild, and Daniela Billi. Sustainable life support on mars–the potential roles of cyanobacteria. *International Journal of Astrobiology*, 15(1):65–92, 2016.

[36] L. Wheeler. Mvb code. `geturl`.

9

Appendix

This appendix provides the graphs that describe the daily variations for all three scenario plotted in Chapter 6. The three cases are the following:

- Worst Case
- Average Case
- Best Case

These cases are represented by a solar longitude of 195, 135 and 75 degrees, respectively. Figure 5.2 represents the worst case scenario and figures 9.1 and 9.2 depict the average and best case scenario, respectively.

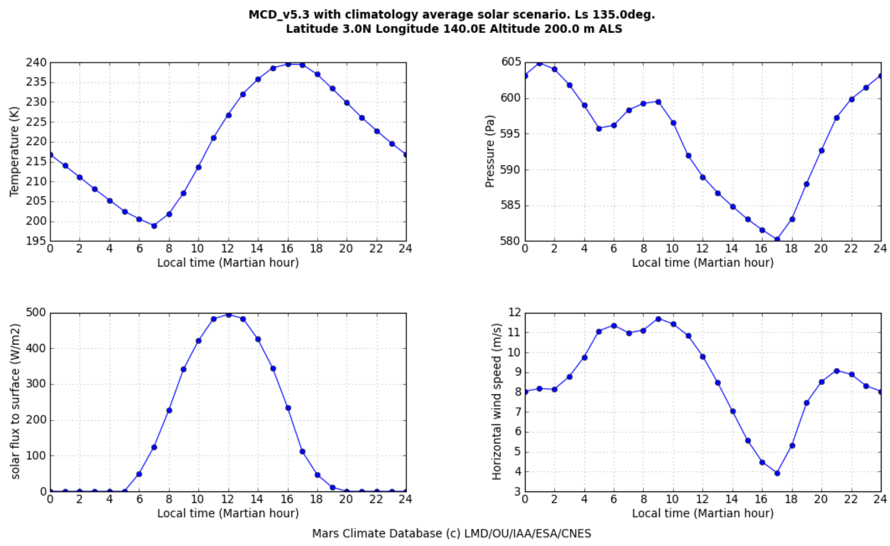

Figure 9.1: Average case scenario graphs occuring at a solar longitude of 135’ throughout an entire Martian day

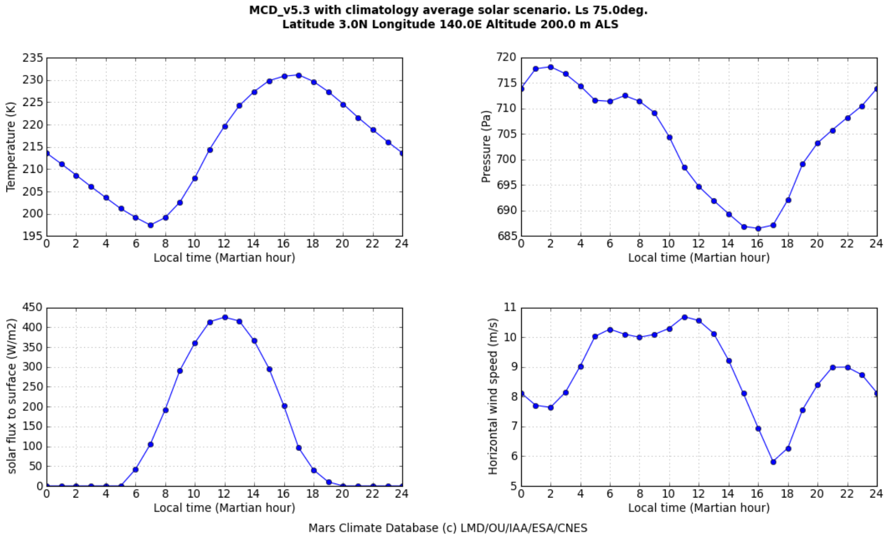

Figure 9.2: Best case scenario graphs occuring at a solar longitude of 75' throughout an entire Martian day