Mars Expedition – Project Hugin & Munin Transfer Vehicles Design

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***Abstract*—The two founders of Pythomspace are planning to land on Candor Chaos on Mars. The objective of this paper is to design a space vehicle to bring the crew from Low Earth Orbit (LEO) to the surface of Mars and back to LEO. The chosen strategy is to have a Transfer Vehicle (TV), able to perform an orbital transfer from LEO to Low Mars Orbit (LMO), where two landers will bring the crew and the cargo onto the Martian surface. One of the landers will then be converted to an ascent vehicle in order to bring the crew back on the TV. The spacecraft will carry all the means necessary to the whole mission, including fuel for the different phases, the life support system and the equipment needed for the Mars surface exploration. A conceptual design is developed, based on the re-usability of the upper stage of Pythomspace's Kang rocket. This design includes the geometry of the station and the subsystems such as propulsion, power generation, thermal management and radiation shielding, and volume needed for the crew and the storage. The TV is made up of 12 Kang upper-stages in total, which are propelled by two Raptor engines and electrically powered by Multi-junction solar cells.**

A conceptual design of the Mars Descent Vehicle (MDV) and Mars Ascent Vehicle (MAV) is conducted. Since the design of these vehicles is strictly connected with the trajectory followed during the relative phases of the mission, the team was also able to design the descent and ascent trajectory.

With the goal of minimizing mass and complexity, the TV is estimated to have a final total wet mass of 655.8 t, including Mars Vehicles which will have a total wet mass of 9.5 t.

***Index Terms*—Mars, Interplanetary, Transfer Vehicle, Mars Lander, Design, Re-usability, LEO, LMO, Ballistic Entry**

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ABBREVIATIONS

ATV	Automated Transfer Vehicle
BNNT	Boron Nitride Nanotubes
CAD	Computer Aided Design
ESA	European Space Agency
EVA	Extra Vehicular Activity
HA	Human Aspects
ICC	Integrated Cargo Carrier
ISRU	In Situ Resource Utilization
ISS	International Space Station
LEO	Low Earth Orbit
LSS	Life Support System
LMO	Low Mars Orbit
MAV	Mars Ascent Vehicle
MDV	Mars Descent Vehicle
MO	Mars Operation
TRL	Technological Readiness Level
TV	Transfer Vehicle

SYMBOLS

A	Area
A_e	Nozzle area
A_{solar}	Surface area of a solar panel
α	Angle of attack
β	Mass flow rate
C_d	Drag Coefficient
D	Drag
Δv	Speed increment for the maneuver
E_{sun}	Solar radiance on Mars
G	Gravitational constant
g	Gravitational acceleration
g_0	Gravitational acceleration on Earth
γ	Flight path angle
η_{solar}	Efficiency of a solar panel
H	Altitude
H_{orbit}	Height of TV in LMO
I_{sp}	Specific impulse
L	Lift
$\dot{m}$	Mass flow rate
m_0	Initial wet mass
m_f	Final mass after thrusting
m_{mars}	Mars' mass
μ	Mars' gravitational parameter
m_p	Propellant mass
m_{walls}	ATV walls' mass
p_a	Ambient pressure
p_e	Exhaust pressure
P_e	Electric power for LSS, computers and communication
P_{solar}	Electric power of a solar panel
R	Volumetric mean radius of Mars
ρ	Density
ρ_{walls}	ATV walls' density
T	Thrust
t_b	Burn time
t_{battery}	Time of battery usage per orbit
t_{orbit}	Time of one lap in LMO
v	Velocity
v_e	Exhaust speed
V_{walls}	ATV walls' volume
W_{min}	Minimum battery capacity
W	Battery capacity
X	Ground distance

I. INTRODUCTION

FROM the Apollo program to the robotic exploration of the Solar System, the Red planet seems to be the next achievement of human spaceflight. If it took 8 days for the Apollo spacecraft to reach the Moon and come back, a journey to Mars will require several months. During that period, the crew must breath, drink, eat, and exercise. The equipment for the exploration must also be brought. Because of all those masses, it is important to design a vehicle that can bring everything in Mars orbit and the crew safely back on Earth. The issue is then the estimation of the amount of fuel required to carry the vehicle, crew and equipment to Mars and back, by reducing the mass carried throughout the mission as much as possible.

Thus, how can a vehicle able to fulfill these requirements be designed? How much fuel will be needed for the trip? How will the crew be able to land safely on the surface of Mars and return to Earth?

To answer those questions, in this report, a conceptual design of a Mars Transfer Vehicle, including two Martian Landers, will be presented. After properly introducing the reader to the problem, the main constraints and assumptions will be given. The methodology will be then thoroughly explained, before showing the main results obtained. Finally the results will be discussed, together with the Technology Readiness Level of the mechanics and science involved in the mission. Then a brief analysis of the Off-nominal Scenarios, Sustainability aspects of the Mission and Choice of the Landing site will be conducted. Finally the main conclusion will be highlighted.

A. *Objectives*

The objective of this report is to design a lightweight transfer vehicle to be used for an interplanetary transportation to Mars. The idea is to make it as simple and low-mass as possible, following the general idea and parameters of the startup *Pythomspace*. The TV will be required to perform an orbital transfer from LEO to LMO, where two descent vehicles will enter Mars' atmosphere and descend on its surface, while the TV will be orbiting the planet. The two MDVs will land on Mars' surface at the designated location, bringing with them the crew and all the required supplies. Then, one of the landers will be converted into a MAV, in order to bring the crew back on the transfer vehicle, ready to leave for Earth. In order to reduce the risks, both the MDVs will be convertible into MAV, however, to be within the given weight limitations, there will only be enough propellant for one ascent vehicle. The entry trajectory is one of the biggest challenges. The vehicle will initially be slowed down using a parachute but the final section of the descent will be propelled, making the timing crucial to avoid too high accelerations during flight or too high velocity at the touch down. The launch will be much more expensive in terms of propellant, with the goal of bringing the vehicle back to the parking orbit with the right velocity to stay on orbit and dock to the transfer vehicle. The aspects analyzed in this report are the design of TV, MDV, MAV, landing and ascent trajectories on Mars.

B. *Constraints*

The payload that can be brought to LEO is limited by the medium-launch system, Kang, which has a payload capacity of $3\,\mathrm{t}$ (pressurized). Furthermore, the upper-stage have a fairing diameter of $2.5\,\mathrm{m}$.

When it comes to the performance, the TV will need to perform different orbital maneuvers through instantaneous impulses. The highest speed increment, Δv, that the engine(s) will need to produce is $3.6\,\mathrm{km/s}$ [1].

Furthermore, there are design constraints for the Mars landers. Both vehicles have a dry mass of $710\,\mathrm{kg}$ and a wet mass of $4750\,\mathrm{kg}$ during descent (unpressurized). One of the landers, the MAV, will be used for the ascent and have a wet mass of $4190\,\mathrm{kg}$. Lastly, each lander's propulsion system consists of six Asterex engines, which use a green liquid propellant, have a specific impulse between 280-310 s and are able to produce a maximum thrust of $12\,\mathrm{kN}$.

C. *Assumptions and Approximation*

The following assumptions were made when modeling the TV:

- Tank to mass ratio at 2% [2]
- The Kang upper stage is 9 m long and is able to provide protection in the outer space
- The green propellant has an I_{sp} of $310\,\mathrm{s}$
- The TV will not be provided with artificial gravity
- Parts of the TV, such as tanks, can be removed easily and safely during the mission
- The maximum Δv required for the mission (3.6 km/s [1]) is achieved by thrusting for 8 min.

The following assumptions were made when modeling the descent/ascent vehicle:

- A parachute and heat shield will be used for the descent
- The parking orbit around Mars is at a height of 230 km and an inclination of 7.25°.

II. Methodology

A. *Transfer Vehicle*

1) Vehicle Configuration: The objective was to build a vehicle that can safely bring a crew of two people from LEO to LMO and back to LEO. The spacecraft had to carry all the necessary resources such as water, food, propellant, Life Support System, and the Mars Vehicles.

The strategy was to build a space station by using the upper stage of Kang as the main structure for both the life module and the fuel tanks. As the Kang was supposed to be pressurized, the structural mass of the module has been computed based on the Automated Transfer Vehicle (ATV) [3], a human-rated vehicle. The Integrated Cargo Carrier (ICC) of the ATV has a structural mass of $5\,\mathrm{t}$ [4] for a global inner volume of $59.74\,\mathrm{m}^3$ with a length of $6.7\,\mathrm{m}$ and an outer diameter of $4\,\mathrm{m}$ [5]. Based on those values, the density of the walls of the ICC was estimated using Eq. (1) for a thickness estimated to be $56\,\mathrm{cm}$.

$$\rho_{\text{walls}} = \frac{m_{\text{walls}}}{V_{\text{walls}}} = 86.73\,\mathrm{kg/m^3} \tag{1}$$

As the inner and outer diameters of the Kang were $2.5\,\mathrm{m}$ and $3.5\,\mathrm{m}$, which gives a thickness of $50\,\mathrm{cm}$, it could be assumed that the walls of the Kang are built with a similar technology as the one of the ATV. The main values for that study are recapped in Fig. 1. Therefore, the structural mass of the Kang upper stage was assumed to be around $3.5\,\mathrm{t}$ for the pressurized module. This structural mass includes radiation shielding for deep space, meteorites and debris protection. However, another alternative would have been to use Boron Nitride Nanotubes

(BNNT) with aluminum for the radiation protection [6]. As this composite is still at a laboratory tested level the impact on the structural mass of this alternative, has been put off to future project work.

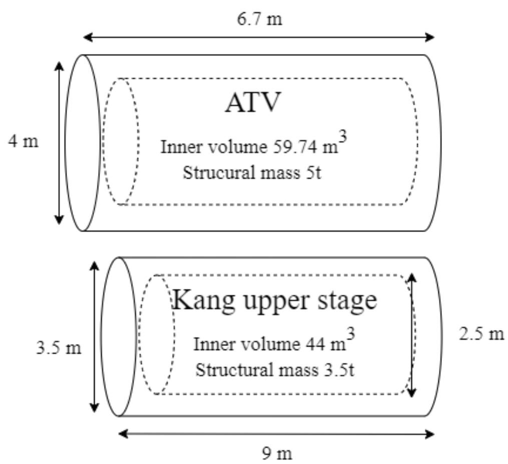

Fig. 1: Characteristics of the ATV compared to Kang

The space vehicle needs to provide a living space with the mass and volume capacity to store the Life Support System (LSS), a connection with the Mars Vehicles (non-pressurized), all the fuel needed for the mission and the power generation system. As the amount of fuel is supposed to be the most burdening contribution to the total mass, the tanks will be removed once empty in order to decrease the dead mass of the station before going back to Earth. Then, all the masses except the amount of fuel were considered as inputs to estimate the mass of propellant, the number of tanks and engines needed. These outputs will also depend on the choices made in the section II-A2 and II-A3.

2) Choice of Propellant: To choose the best type of propellant suitable for the mission, three different combinations have been analyzed and compared:

- Green propellant (Furfuryl Alcohol and White fumes of Nitric Acid)
- Liquid Hydrogen and Liquid Oxygen
- Liquid Methane and Liquid Oxygen

The reasons behind narrowing down the choice to these three types of propellants are: for Green Propellant, to try and have as low toxic emissions as possible, for Hydrogen and Oxygen, to have as high I_{sp} as possible, for methane, to have an intermediate I_{sp} and a fuel that did not require particular conditions to be stored for a long time. In Table I the I_{sp} used for the different propellants can be found.

Table I: Specific impulse for different propellants.

Propellant	I_{sp}[s]
FFA + HNO3	310
LH2 + LOX	448.5
LCH4 + LOX	375

Tsiolkovsky rocket equation (2) was used to determine the variation of Δv with the wet mass of the spaceship.

$$\Delta v = v_e \ln\left(\frac{m_0}{m_f}\right) = I_{sp} g_0 \ln\left(\frac{m_0}{m_f}\right) \tag{2}$$

The three propellant combinations were then compared through the graphs to find the one that allowed the lower wet mass for the same Δv. During this computation, all the masses were kept constant, except for the masses of the propellant tanks. The values used for the computation [7], [2] can be found in Table II.

Table II: Masses of propellant tanks.

Propellant	Tank Mass
FFA + HNO3	1.264 t/u
LH2 + LOX	2.462 t/u
LCH4 + LOX	1.264 t/u

3) Propulsion System: The propulsion system is required to perform high-thrust maneuvers and be compatible with the propellant considered in Section II-A2. Hence, three engines have been considered and are listed in Table III.

Table III: Characteristics of different engines.

Description	Asterex	RL10C-1 [8]	Raptor [9], [10]
Propellant	FFA + HNO3	LH2 + LOX	LCH4 + LOX
Mixture ratio (O/F)	2.56	5.5	3.6
Thrust	12 kN	102 kN	1 900 kN
Specific impulse	310 s	450 s	375 s
Nozzle diameter	–	1.45 m	2.4 m
Dry mass	–	190.5 kg	2 000 kg

The Pythomspace Asterex engine is considered as the first candidate because it is planned to be used by Pythomspace themselves for their Mars expedition. It is fueled by green propellant (FFA + HNO3) and has completed successful hot tests [11]. The Aerojet Rocketdyne RL10C-1 engine is a cryogenic liquid fuel (LH2 + LOX) engine that is currently used on the upper stage of the United Launch Alliance's Atlas V rocket and is slated to power National Aeronautics and Space Administration's (NASA) Space Launch System, which is planned to be used to build a base on the moon as well as sending humans to Mars [12]. The RL10 series have powered space exploration vehicles for more than a half a century, thus making it a highly reliable propulsion system and a suitable candidate for the mission [8]. Lastly, the SpaceX Raptor engine is the third candidate since it powers both the lower and upper stage of SpaceX' interplanetary transport system that will send humans to Mars: the Super Heavy booster and Starship. Raptor is also a cryogenic liquid fuel (LOX + LCH4) engine and has completed several suborbital test flights [10]. It is a significant improvement of the company's successful Merlin engine used on Falcon 9 and Falcon Heavy, thus making it a valid candidate for the mission.

To determine the type and number of engines, the generated thrust from the propulsion system must be greater than the maximum required thrust to complete the mission. The required thrust can be calculated according to:

$$T = \dot{m} v_e + (p_e - p_a) A_e \tag{3}$$

where $\dot{m}$ is the mass flow rate, v_e is the exhaust velocity, A_e the nozzle area and p_e and p_a are the exhaust and ambient pressure respectively. Since the engines are adapted to vacuum conditions, $p_e = p_a$ and Eq. (3) reduces to the first term. By substituting v_e from Eq. (2) to Eq. (3) and taking into consideration that the mass flow rate is defined as the amount of propellant m_p being expelled over the burning time t_b, the required thrust is defined by Eq. (4):

$$T = \frac{m_p \Delta v}{t_b \ln\left(\frac{m_0}{m_f}\right)}. \tag{4}$$

The minimum amount of propellant that will be needed for the propulsion system to achieve the required speed increase and thrust can be calculated by rearranging Eq. (2):

$$m_p = m_0 \left(1 - \exp\left(\frac{\Delta v}{I_{\text{sp}}\ g_0}\right)\right). \tag{5}$$

4) Electrical Power System: The electrical power system has to provide $2.655\,\text{kW}$ constant electrical power for the LSS [6] as well as $0.359\,\text{kW}$ for computer- and communication systems [13], summing up to $P_e = 3.014$ kW constant electrical power. During the transfer from LEO to LMO the spacecraft can permanently use sunlight for solar-electric power P_{solar}. The further away the TV moves from the Sun, the lower is the Sun irradiance. At the end of the transfer, the Sun irradiance E_{sun} in LMO will be $586.2\,\text{W/m}^2$ [14]. The resulting solar electric power depends on the surface area of the solar panel A_{solar} as well as its efficiency η_{solar} and can be calculated as defined by Eq. (6):

$$P_{\text{solar}} = E_{\text{sun}} A_{\text{solar}} \eta_{\text{solar}}. \tag{6}$$

In LMO the TV experiences eclipse phases, in which sun light cannot be used for power generation. Therefore, batteries have to cover the demand on electrical power during eclipse phases. The needed capacity is determined by the time of an orbital run, evaluated from Eq. (7):

$$t_{\text{orbit}} = 2\pi \sqrt{\frac{(R + H_{\text{orbit}})^3}{\text{Gm}_{\text{mars}}}}. \tag{7}$$

During the Sun phase of an orbit, the solar panels have to recharge the batteries and still be able to generate enough power for all electrical systems of the TV. With $t_{\text{orbit}} = 110$ min and the ratio of an eclipse phase to a Sun phase on the International Space Station (ISS) being 0.39 [15], the battery time t_{battery} can be estimated to 43 minutes leading to a minimum battery capacity of $W_{\text{min}} = 2.16$ kWh. The minimum required solar electric power can then be calculated to $P_{\text{solar}} = 5$ kW by Eq. (8):

$$P_{\text{solar}} = \frac{P_e(t_{\text{orbit}} - t_{\text{battery}}) + W_{\text{min}}}{(t_{\text{orbit}} - t_{\text{battery}})}. \tag{8}$$

Off-nominal states, where the solar panels are not working in a normal way, have to be considered for the battery capacity as well as the battery lifetime depending on cycles and the depth of discharge. One off-nominal scenario for the malfunctioning of the solar panels is treated in Section IV-B.

As solar panels generate not only electricity but also heat, radiators have to be provided for heat dissipation. Because of logistic reasons the dimensions and the mass of solar panels, batteries and radiators should be minimized. Therefore the efficiency of batteries, solar panels and radiators has to be maximized. Possible failures of parts of the electrical system have to be taken into account. In case of a partial failure of the electrical system, it still has to be able to provide enough power for safety-critical systems like the LSS.

B. Mars Vehicles

In this subsection the conceptual design of the MAV and the MDVs will be presented, focusing on the external configurations and highlighting those that are the most relevant components during the ascent and the descent trajectory.
The mission is designed to bring two different vehicles on Mars' surface, MDV 1, which will be unmanned, and MDV 2, the manned one, which will be carrying the crew. Both of them were designed in order to be converted into MAV to reduce the risk of remaining stuck on the surface. However, there will be enough space to bring the propellant for only one ascent. The names given to MDV 1 and MDV 2 for the mission are, respectively, Olympus 1 and Olympus 2.

1) Mars Descent Vehicles Configuration: The descent into Mars' atmosphere is a critical phase of the mission, which should be hazardous both for the humans and for the vehicles. For this reason, the design of both the MDVs, which will have exactly the same volumes and masses, is highly dependent on the requirements of the trajectory. The external structure of the vehicles will be entirely made of Aluminum composite material reinforced by BNNT [16], a material which has been recently tested by NASA with the aim to use it in harsh space environments, characterized by a very low density and an incredibly efficient radiation protection. [17] During the reentry, the vehicle will also be protected by an ablative heat shield made out of PICA (Phenolic-Impregnated Carbon Ablator) [18]. The lightness and the efficiency in the thermal protection make this material extremely suitable for the mission, and, in addition, it has been tested and used in various applications by NASA and SpaceX. Initially, the atmospheric entry will essentially be a ballistic trajectory, with no propulsion or extra devices to control the followed path, however, the design of the vehicle itself will contribute to defining an appropriate descent. In fact, from the shape of the capsule and the ratio between the maximum radius and the height of the vehicle consent to produce a certain amount of lifting force, for an overall aerodynamic efficiency, L/D, of 0.2. The velocities and the accelerations reached during the descent will be extremely high, for this reason the use of a parachute results to be essential. The parachute will be stored in an apposite semi-spherical volume on the top surface of the capsule, which will then be ejected at the moment of the parachute deployment. The maximum diameter of the parachute is $20\,\text{m}$, with a disc-gap-band configuration made out of polyester and nylon [19], but thanks to modern technologies, [20], the necessary storage volume will be extremely small and compact. In the final part of the descent, the retro-propulsion will be essential in order to touch the ground at a reasonably low speed. In order to activate the engines, the lower aeroshell will be ejected during the descent with the parachute, some supports will be deployed and the engines will then have the chance to be powered.

2) Mars Ascent Vehicle Configuration: One of the two MDVs will be converted into the MAV to bring the crew back to the parking orbit. Depending on the conditions after landing, the MDV to be converted into MAV will be selected and the required propellant, which was initially equally distributed between the two MDVs, will be moved to the future MAV. For this reason, the MDVs will be both equipped with a pouring system, to make the filling up process possible. The conversion into MAV, apart from the pouring of propellant, is mainly represented by the removal of the remaining part of the aeroshell. In the ascent phase of the mission on Mars, the aerodynamic properties of the vehicle will not be as essential as during the descent.

3) Propulsion System and Choice of Propellant: The Mars Vehicles are equipped with six Asterex engines, providing 5 kN of constant thrust each. The propulsion system is powered by green fuel, presented in Section II-A2, with a Fuel/Oxidizer ratio of 0.39, which is translated in a ratio between the volumes of the tanks equal to 0.29 [21]. The choice of the engines and the propellant has been mainly made in order to be as consistent as possible with the *Pythomspace* conceptual design of the vehicles. In addition, the green propellant will reduce the human impact on Mars' surface and, thanks to its higher density when compared to the other propellants in Table I, the tanks have much lower volume, which is highly relevant for these vehicles of small dimensions. As expected, the ascent phase of the mission will be the most demanding in terms of propellant, so the tanks of the MDVs were sized in order to be able to carry enough propellant for the ascent. For this reason, during the descent, not all of the available volume of the tanks will be used.

C. Mars Trajectory

In this section, the trajectory of the ascent and descent vehicles will be discussed. To design the trajectory, a model of Mars' atmosphere by NASA [22] was used: the temperature, density and pressure depending on the altitude to the Martian surface is therefore known. The Mars atmosphere is set to begin at a height of 100 km. According to the hypothetical case for Pyhtomspace, the landing and launch site will be at Candor Chaos (7.25°S 72.25°W) at an altitude of $-4500\,\mathrm{m}$. This low altitude will help the descent with a higher atmosphere density.

1) Descent Trajectory: The MDV1 (the unmanned vehicle) will first begin the descent on Mars. After confirming that the descent of the MDV 1 is successful, the MDV 2 (manned vehicle) will follow with the same trajectory. Therefore, only one descent trajectory was designed for both descent vehicles. The trajectory consists of several phases:

- From the parking orbit, the vehicle will perform a thrust maneuver to reduce its periapsis altitude and begin the entry phase.
- The vehicle will enter the atmosphere with a certain velocity V_{entry} and angle γ_{entry} relative to the local horizon. This is the start of the ballistic entry. The heat shield is crucial during this phase as the vehicle will experience high levels of heating.
- After experiencing the maximum drag pressure, the parachute will be deployed with a reduced diameter of $8\,\mathrm{m}$ and $40\,\mathrm{s}$ later, the parachute will expand to its total diameter of $20\,\mathrm{m}$. This is done to reduce the high deceleration load on the crew. During this phase, the heat shield will be dropped to reduce the weight of the vehicle.
- Finally, after dropping the parachute, the six Asterex engines will ignite in order to land safely on the Martian surface. The thrust will be assumed constant for this phase.

To simulate the descent trajectory, Eq. (9)–(13) were used:

$$\frac{\mathrm{d}v}{\mathrm{d}t} = -\frac{T}{m} - \frac{D}{m} - \mathrm{g}\sin(\gamma) \tag{9}$$

$$\frac{\mathrm{d}\gamma}{\mathrm{d}t} = -\frac{1}{v}\left(\mathrm{g} - \frac{\mathrm{v}^2}{\mathrm{R}+\mathrm{H}}\right)\cos(\gamma) + \frac{\mathrm{L}}{\mathrm{mv}} \tag{10}$$

$$\frac{\mathrm{d}X}{\mathrm{d}t} = v\cos(\gamma)\frac{R}{R+H} \tag{11}$$

$$\frac{\mathrm{d}H}{\mathrm{d}t} = v\sin(\gamma) \tag{12}$$

$$\frac{\mathrm{d}m}{\mathrm{d}t} = -\beta \tag{13}$$

The drag was calculated with Eq. (14).

$$D = \frac{1}{2}C_D\rho A v^2 \tag{14}$$

The gravitational field depends on the altitude according to Eq. (15).

$$g = \frac{\mu}{(\mathrm{R}+\mathrm{H})^2}. \tag{15}$$

During the descent, as the vehicle isn't going straight down, the parachute will not be aligned with the velocity of the vehicle. Therefore, the parachute won't be as effective: the efficiency of 0.6 for the parachute area was assumed to take this phenomenon into account.

2) Ascent Trajectory: The one stage ascent vehicle will need to reach the 230 km height circular orbit in order to dock with the main spaceship and return to Earth. To reach this circular orbit, the final path angle and velocity were calculated using Eq. (16) and (17):

$$\gamma_{\text{final}} = 0 \tag{16}$$

$$v_{\text{final}} = \sqrt{\frac{\mu}{\mathrm{R}+\mathrm{H}_{\text{orbit}}}} \tag{17}$$

The ascent vehicle will launch to the east. The velocity gain thanks to the rotation of Mars was taken into account at the end of the simulation of the trajectory. Eq. (9) and (10) were slightly modified to Eq. (18) and (19):

$$\frac{\mathrm{d}v}{\mathrm{d}t} = \frac{T}{m}\cos(\alpha) - \frac{D}{m} - g\sin(\gamma) \tag{18}$$

$$\frac{\mathrm{d}\gamma}{\mathrm{d}t} = -\frac{1}{v}(g - \frac{v^2}{\mathrm{R}+\mathrm{H}})\cos(\gamma) - \frac{T}{mv}\sin(\alpha) \quad (19)$$

Where α is the angle between the thrust of the engines and the velocity of the vehicle. As the thrust is aligned with the longitudinal axis of the vehicle, this is equivalent to rotating the vehicle with the angle α. The usual gravity turn maneuver, which makes the vehicle turn during the ascent thanks to gravity, is harder to achieve in this case as the gravitational field of Mars is about three times lower than the gravitational field of the Earth. That is why some fuel is used to reduce the flight path angle.

III. Results

A. Transfer Vehicle

1) Choice of Propellant: Thanks to the graphs shown in Fig. 2 and 3, it was possible to note that the Green Propellant is only good for a mission that requires a low Δv and payload capacity, but for a longer mission with higher Δv, the wet mass of the spacecraft would have been too high, due to low I_{sp}. Hydrogen, though having a really high I_{sp}, requires particular storability conditions in its liquid form. The propellant tanks were so heavy in this case [7] that the benefits deriving from such high I_{sp} were nullified. Furthermore, the number of propellant tanks was too high to make them fit all in the vehicle. Lastly, methane could allow the best compromise between tank mass and number and I_{sp}, resulting in the lower wet mass for the mission.

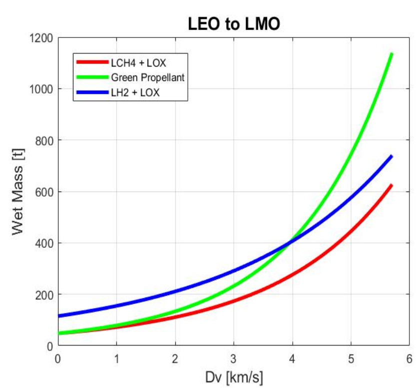

Fig. 2: Comparison of different propellants' performances - LEO to LMO

2) Propulsion System: Based on Section III-A1, the propellant of choice for the TV is LOX + LCH4. This results in the SpaceX Raptor engine being the most suitable engine for the mission.

The propellant mass needed to achieve the required maximum speed increase is determined using Eq. (5) to approximately $390.5\,\mathrm{t}$.

The required thrust for the mission is then calculated using Eq. (4). With a speed increase of $3.6\,\mathrm{km/s}$, a required propellant mass of $390.5\,\mathrm{t}$, a burn time of $480\,\mathrm{s}$, and a mass ratio of 2.66 the required thrust is $2993\,\mathrm{kN}$. Since the vacuum adapted Raptor engine can produce a thrust of $1900\,\mathrm{kN}$, the propulsion system needs to consists of 2 Raptor engines.

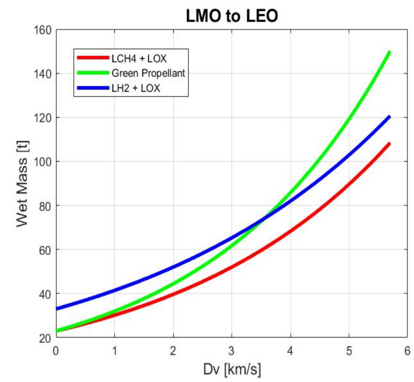

Fig. 3: Comparison of different propellants' performances - LMO to LEO

Table IV: Mass Contributions on electrical power system

System	**Mass [kg]**
Multi-junction solar panels	96
Gimbals	16
Li-Ion batteries	72.4
Power management system	8
Radiators	124
Total mass	316.4

3) Electrical Power System: The mass distribution of the electrical power system is presented in Table IV.

The solar panels have to put out at least $P_{\text{solar}} = 5\,\mathrm{kW}$ electrical power. For higher mission safety two individual panels, each producing $5\,\mathrm{kW}$, are chosen for the TV. If one of the panels gets damaged and can't deliver its maximum power anymore, the other panel can still provide enough power for the TV itself. Together both panels could provide $10\,\mathrm{kW}$ electrical power. Multi-junction solar cells are the most efficient type of solar cells and are therefore chosen for the TV, as their efficiency $\eta_{\text{solar}} = 46\%$ [23] is much higher than $\eta_{\text{solar}} = 20.3$-$25\%$ [24], [25] of crystalline silicon cells or $\eta_{\text{solar}} = 25\%$ [26] of gallium arsenide-based cells.

With the sun irradiance of $E_{\text{sun}} = 586.2\,\mathrm{W/m^2}$ [14] on mars, each multi-junction cell panel's surface area has to measure $A_{\text{solar}} = 18.54\,\mathrm{m^2}$ by rearranging Eq. (6). The mass of each panel can be estimated by the mass of an ISS's solar panels and its surface area by the ratio of both surface areas being 18.54/420 [27]. With $1088\,\mathrm{kg}$ as the mass of one ISS's panel [28], the mass of each panel for the TV is assumed as $48\,\mathrm{kg}$. Like the ISS, the panels can be folded for easier transportation or stored away if not needed. Each panel is mounted on a two-axis gimbal to be able to face the sun in a specific angle. The mass of each gimbal is estimated to be $8\,\mathrm{kg}$ [29].

ISS's battery capacity could cover one complete orbit in case the solar power generation fails [15]. As the TV will only be inhabited by two crew members, the time needed to repair parts of the electrical system might be longer. Therefore the batteries have to be able to cover $6\,\mathrm{h}$ of time without solar power generation. With a constant consumption of $3.014\,\mathrm{kW}$ the capacity W needs to be $18.1\,\mathrm{kWh}$, being more than eight times as big as $W_{\min}$. Because the mass of the TV has to be as low as possible, the type of battery has to be as efficient as possible. Lithium-Ion batteries have the highest specific energy of up to $250\,\mathrm{Wh/kg}$ [30] and are therefore chosen for the TV. The capacity is provided by two individual Lithium-Ion batteries with a capacity of 9.05 kWh and a mass of $36.2\,\mathrm{kg}$ each. If one of the batteries failed, the TV could still be powered $3\,\mathrm{h}$ without solar panels. In every eclipse phase one of the batteries experiences a discharge of $W_{\min}$, which is $24\,\%$ of one's total capacity. According to [31] at $24\,\%$ depth of discharge, the battery lifetime of the Lithium-Ion battery will be 35 000 cycles, leading to 2675 days in LMO.

A power management system will decide when to charge or discharge the batteries. In addition to that, the system distributes the generated power of the solar panels and sets the gimbal angles regulating the generated power. Scaled down from another Mars mission [29], the system mass is estimated to be $8\,\mathrm{kg}$.

The heat generated in the process of power generation, distribution and usage is dissipated via radiators. ISS uses radiators capable of $56\,\mathrm{kW}$ heat dissipation for $240\,\mathrm{kW}$ solar panels [32]. As the TV is equipped with 10 kW solar panels, radiators have to be able to dissipate $2.33\,\mathrm{kW}$ of heat. Therefore two radiators each dissipating $1.17\,\mathrm{kW}$ are fitted on the TV. Scaling down ISS's radiators [32], the radiators will have a surface area of $3.5446\,\mathrm{m}^2$ and a mass of $62\,\mathrm{kg}$ each.

The two extracted multijunction-solar panels and two radiators on the TV are shown in Fig. 4.

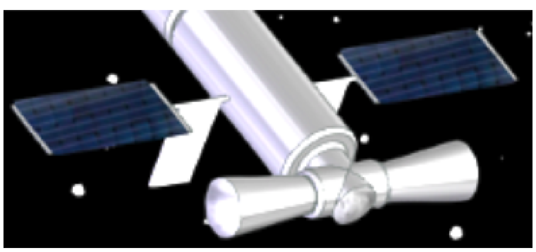

Fig. 4: Extracted Multi-Junction Solar Panels and Radiators

4) Vehicle configuration: Table V presents the masses needed for the different subsystems of the mission. In order to store the mass of fuel, composed of $476.15\,\mathrm{t}$ liquid oxygen and $131.89\,\mathrm{t}$ of liquid Methane 11 tanks were required with a distribution for presented in Table VI. An overview of the Computer Aided Design (CAD) models of the Transfer Vehicle configuration, both during Earth-Mars and Mars-Earth trajectories, is shown in Fig. 5 and Fig. 6

Table V: Mass Contributions on TV

System	**Mass [t]**
MDVs	9.5
Human Aspects	14.4
Power and Communication, Thermal Control, Solar Arrays	0.4857
Robotic Arm	1.6
Engines, Attitude Control	4.4
Propellant tanks	12.8
Structural mass of pressurized module	3.5
Total dry mass	133.2
Propellant mass (with 5% more for reliability)	579.1 (608.1)
Total wet mass	626.8
Total wet mass for reliability	**655.8**

Table VI: Fuel repartition

Phases	**Number of tanks**	**Tank's capacity [t]**
From LEO to LMO	8	70.53
From LMO to LEO	3	28.46

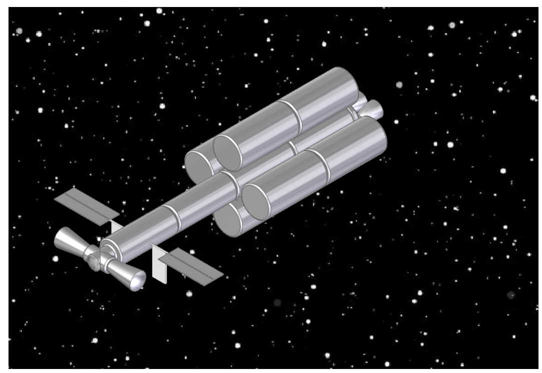

Fig. 5: TV during Earth-Mars trip

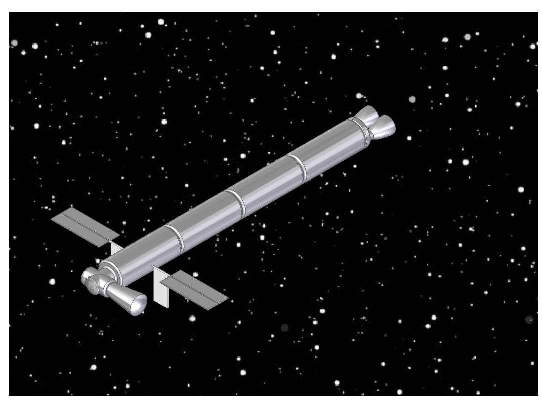

Fig. 6: TV during Mars-Earth trip

B. Mars Vehicles

In Table VII and VIII the relevant mass contributions are highlighted.

The relevant geometrical dimensions of the MDVs are represented by the maximum diameter of the Aeroshell, which is equal to $2.5\,\mathrm{m}$, the height of the vehicle of $4\,\mathrm{m}$ (excluding the Asterex engines) and the parachute slot, a hemispheric volume with $46\,\mathrm{cm}$ of diameter. The interiors of the Vehicles will be designed by the Mars Operation (MO) subteam [17]. Please note that the masses in Tables VII,VIII and IX about the LSS and MO are taken from the final calculations provided by the other subteams: MO [17] and Human Aspects (HA) [6]. In the remaining available mass of the MDVs, some extra propellant has been allocated in case of emergency during the trajectories, as a safe margin for the performed calculations and to cover possible leaks during the pouring into the MDV that will be converted into MAV.

Table VII: Mass breakdown structure for MDV 1 (unmanned).

Description	Mass [kg]
Parachute	50
Heat Shield	500
Structure	570
Crew	0
Space Suits	0
MO	409
LSS	261
Propellant	2592
Extra propellant*	368
Total wet mass	**4750**

*This value includes the Pouring System.

Table VIII: Mass breakdown structure for MDV 2 (manned).

Description	Mass [kg]
Parachute	50
Heat Shield	500
Structure	570
Crew	140
Space Suits	72
MO	197
LSS	261
Propellant	2592
Extra propellant*	368
Total wet mass	**4750**

*This value includes the Pouring System.

The final conceptual design of the MDVs respectively during reentry and powered descent is shown in Fig. 7 and 8. In Fig. 9 the MAV is presented in the pre-launch configuration. The mass breakdown structure is presented in Table IX.

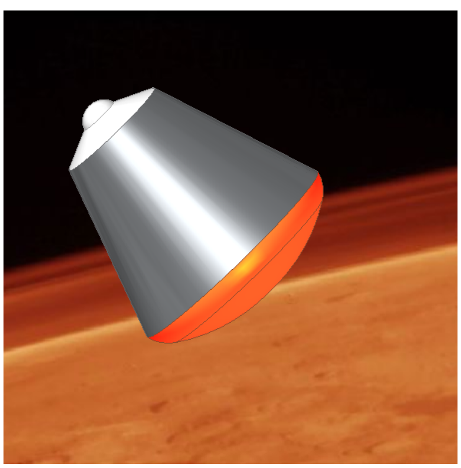

Fig. 7: MDV capsule during reentry

C. Mars Trajectory

1) Descent trajectory: The crew will experience the highest deceleration during the deployment of the parachute. This deployment has been designed so the crew will experience reasonable and not life threatening loads. The peak deceleration of 6.7 g has been considered sustainable for the trained crew. The plot of the descent trajectory is shown in Fig. 10–12:

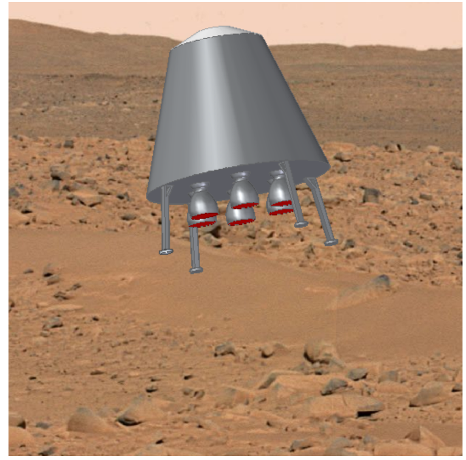

Fig. 8: MDV during powered descent

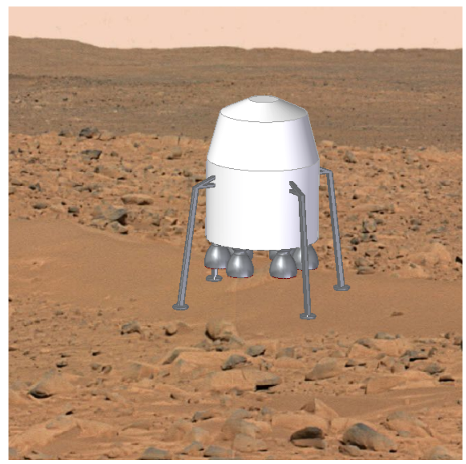

Fig. 9: MAV before launch

Table IX: Mass breakdown structure for MAV (manned).

Description	Mass [kg]
Structure	570
Crew	140
Space Suits	72
MO	10
LSS	0
Propellant	3398
Total wet mass	**4190**

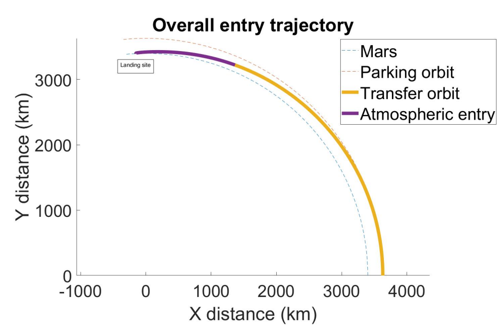

Fig. 10: The overall trajectory of the descent

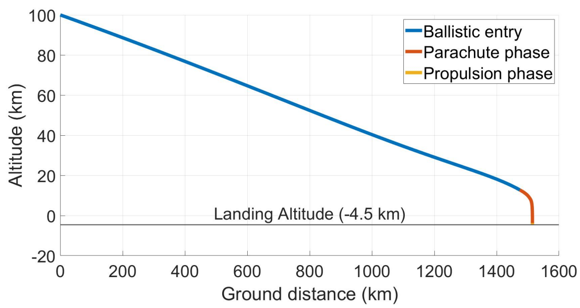

Fig. 11: The trajectory of the descent through the Martian atmosphere

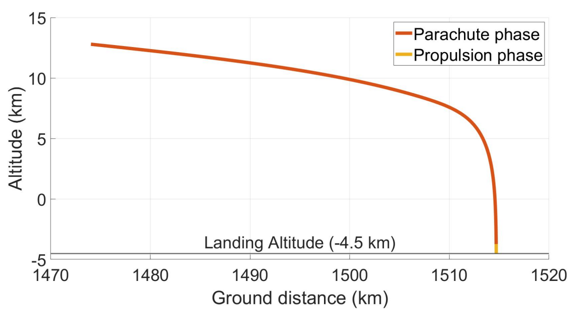

Fig. 12: Final stages of the descent

Table X displays relevant data concerning the descent:

Table X: Descent data

Description	Value
Initial Δv thrust (km/s)	- 0.1
Initial angle with respect to the landing site (°)	92.6
Atmospheric entry Velocity (km/s)	3.46
Atmospheric entry Angle (°)	- 3.09
Max deceleration	6.7 g
Time with high deceleration (greater than 3g) (s)	14
Altitude parachute deployment (km)	12.8
Altitude engines firing (km)	- 3.76
Burning time (s)	19.2
Final altitude (km)	- 4.5
Atmospheric descent time	11 min 44 s

2) Ascent trajectory: The plot of the ascent trajectory is shown in Fig. 13:

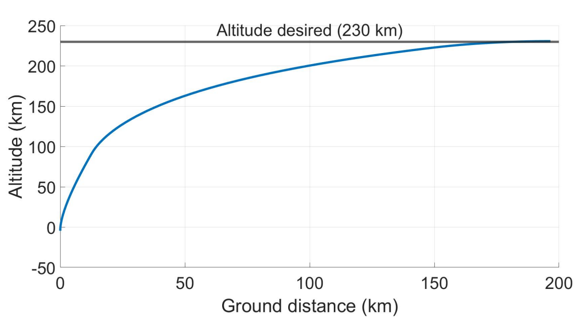

Fig. 13: Trajectory of the ascent

Table XI shows relevant data concerning the ascent.

Table XI: Ascent data

Description	Value
Burning time (s)	338
Initial altitude (km)	-4.5
Final altitude (km)	230
Final velocity (km/s)	3.49
Max acceleration	3.6g
Time with high acceleration (greater than 3g)	21 s

After the ascent, 10 s worth of fuel is remaining as a safety margin. Near the end of the ascent as the vehicle gets lighter and lighter, the acceleration reaches its peak. Table XII summarize the different Δv of the ascent.

Table XII: Δv's data for the ascent

Δv	[km/s]
Propulsion	4.83
of which used to turn	0.543
Gravity	1.10
Drag	$6.57.10^{-3}$
Rotation of Mars	0.239

Compared to the gravity losses, the drag losses are negligible and the ascent could have been safely assumed without the Martian atmosphere. As the gravity turn is harder to perform on Mars, a fair amount of fuel is used not to increase the velocity but to turn the aircraft during the ascent. A bit of velocity is gained by launching to the east.

IV. Discussion

A. Technology Readiness Level

Technological readiness level (TRL) is a set of indicators that measures the maturity of the technology being developed. Based on NASA criteria, TRL is divided into nine levels, on which TRL 1 being the lowest level and TRL 9 being the highest level. To achieve the highest TRL level, the technology is required to be "flight proven" through a successful mission.

The core of the proposed conceptual design of the TV is made out of the upper stage of Pythomspace's rocket Kang. Kang is not yet developed, yielding a low TRL. However, a lot of inspiration regarding dimensions and structure have instead been derived from the European Space Agency's (ESA) ATV which has been in operation for 7 years.

As for the propulsion system and the electrical power system, both systems consist of technologies that are used on spacecraft today and have been proven to work. The Raptor engine is a further iteration of SpaceX's Merlin engine that has made historical success with its reusability. Raptor itself has already demonstrated successful launches and by the time that the mission is going to be conducted (2026 at latest), the technology will have matured even more.

A detailed investigation of how all the components (tanks, airlock, solar arrays, etc.) of the vehicle are going to be attached to each other as well as of how the interface between different subsystems (propulsion system, electrical power system, LSS, etc.) is going to look like, have not yet been conducted. Since the technology concept has been formulated through an analytical study, the design of the TV presented in this paper is on TRL 2.

Regarding the Mars vehicles, some of the main components such as the parachute and the heat shield have already been tested and materials and geometry have been certified to work as expected in Martian conditions. However, there are some technologies which are still in development, such as BNNT material for radiative protection, the Asterex engines and the Green Propellant. Regarding the BNNT, there are a number of studies showing that it will be able to provide the required structural properties and radiation shielding. Nevertheless, since it has never been tested in the conditions of the Mars atmosphere, there is no certainty of success since many other factors might deteriorate the theoretical properties of the material. On the other hand, the Asterex engines have been tested by *Pythomspace* with green propellant, so the foreseen performances can be considered quite accurate. In addition, the safety margin applied to the performances during the design of the mission, which increases the probability of actually achieving them with the selected technologies. Overall, the TRL for the Mars Vehicles might be considered on an high-average level of 6.

B. Off-nominal scenario

Some off-nominal scenarios have been taken into account during the design of the TV:

- There is a possibility that the solar arrays get stuck during the deployment if the gimbal stops working. In this case the astronauts would be required to wear their suits and do an Extra Vehicular Activity (EVA) to fix the panels manually.
- As regards the engines, two raptors are located on the TV, but their combined maximum thrust is required just for the first stage of the mission: escaping from Earth. After this Δv has been completed, one of the engines will act as backup in case there are issues with the main one.
- One full propellant tank has been designed to fit in the vehicle as backup in case extra propellant is needed for correction maneuvers.

As regards the MDVs, they will be provided with extra propellant with respect to the nominal required amount considered for the descent and ascent trajectories. Since some assumptions have been made to compute them, a higher amount of propellant might be needed for various reasons, i.e. particular weather conditions or approximation errors. Another reason to equip the Mars Vehicles with extra propellant is that the filling of MAV's tanks might lead to some leaks, due to a realistic efficiency factor of the pouring system. Finally, the I_{sp} of the Green Propellant might oscillate slightly towards lower values and this might as well lead to a higher amount of required propellant during the descent and the ascent trajectories.

C. Sustainability

Three choices strongly impact on the sustainability of the TV design:

- Detached propellant tanks before the return phase of the mission
- One MDV left on Mars surface
- Choice of propellant

The empty propellant tanks were chosen to be separated from the vehicle before returning to Earth in order to decrease the mass of the TV by avoiding carrying dead mass and therefore save fuel. The MDV will be left on Mars' surface for the same reason, but also in order to have more mass available to the subteams MO and to HA. If it was decided, in fact, to bring the MDV back to the TV, the propellant mass carried on Mars surface would have increased, thus decreasing the available payload. As regards the choice of propellant, Methane and Oxygen react and produce Carbon Dioxide and Water and can therefore be considered as green fuels, as shown in Eq. (20).

$$\mathrm{CH_4} + \mathrm{O_2} \rightarrow \mathrm{H_2O} + \mathrm{CO_2} \tag{20}$$

The Kang launcher propellant is made of Furfuryl Alcohol and White fumes of Nitric acid, according to Pythomspace design, which is the same propellant used for the MDVs and MAV. This means that every type of propellant used throughout the mission can be defined as "Green Propellant", thus not causing any toxic emission both in Earth and Mars's atmosphere. Furthermore, in a future development of the mission, part of Methane could be produced by a *Sabatier*-like process, but can also be found on Mars surface: an In Situ Resource Utilization (ISRU) could be performed for a future mission and the fuel produced on the Red Planet.

D. Choice of the landing site

Candor Chaos has been chosen to be the landing site due to its low altitude which should help the descent thanks to the denser atmosphere of Mars. However, after computing the trajectories and according to the Mars atmosphere model used, this landing site provided no significant benefits in terms of burning time, or in terms of reducing the terminal velocity of the descent vehicle compared to a more standard landing site. Moreover, Candor Chaos, as a landing site, has many drawbacks. For example, due to its relatively small size, the trajectory will need a great precision compared to a landing on a plain. The crew operations will be a lot harder to perform on a canyon and the relief around the landing site will result in reduced communications and sun exposure.

V. Conclusion

To conclude, the major challenge to create a vehicle that can bring a crew of two people was to minimize the mass to reduce the required amount of fuel. The total wet mass of the vehicle was estimated to be around $655.8\,\mathrm{t}$ with $93\,\%$ of fuel composed of LOX and $\mathrm{LCH_4}$. However, future work on structures with radiation protection can be done to minimize the structural mass by using BNNT, same as it was estimated for the MDVs. Furthermore, an analysis of the connections between the different parts of the TV should be investigated more closely during future work. As regards the Mars Vehicles, further and deeper analysis should be conducted to better estimate the required structural mass. The very high accelerations and the thermal impact of the atmosphere are only a few of the main challenges connected to a landing on Mars surface. However, with the objective to keep the mission as simple as possible, the design of the presented vehicles, is an exact conceptual solution to the problem. All the main human related factors of the vehicles have been, in fact, taken into account, and all the constraints on the wet masses have been observed. In terms of trajectory, considering the shown assumptions, the model provides a good level of accuracy, with the assurance of landing in the desired location. However, for future missions, another landing site could be considered to simplify the process and increase the time-window for the beginning of the descending part. In conclusion, it has to be highlighted that the design of the TV is able to support an even longer stay on the Martian surface and the fuel can be produced on Mars surface with the suitable equipment. The vehicle will stay in a parking orbit at its return to Earth, ready to be refueled and reused when necessary.

VI. Division of Work

Maria Pilar Alliri performed the study of the transfer vehicle design, made the CAD of the TV, with emphasis on the choice of propellant and off-nominal scenario parts; also was the Team Leader, acting as a communicator with the other teams.

Robin Duprat performed the study of the transfer vehicle design with estimation of the structural mass and global configuration of the vehicle.

Jennifer Ly performed the study of the transfer vehicle design, with emphasis on the propulsion system, and did initial research of the electrical power system design.

Moritz Disson performed the study of the electrical power system and thermal control system by finding necessary solar arrays, batteries and radiators for a nominal and off-nominal scenario.

Ludovico Bravetti designed the Mars vehicles, MDVs and MAV, also performing their CAD model, providing them with all the components required during the mission.

Mounib Bouaïssa formulated the equation of motion for descent and ascent phase trajectory analysis into MATLAB codes and performed the simulation.

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