Mars UPV Team

Technical Report 0001

Feasibility Study Of A Jet-pack System For Mars Operations

Valencia, April 24, 2016

Feasibility Study Of A Jet-pack System For Mars Operations

Mars UPV Team, 2016

Abstract

From superhero movies to video-games we have tried to imagine an individual jet propulsion system to fly on our own. We have several attempts of this system over the world, but why don't we apply this technology to the exploration of Mars? In this paper we are going to develop the mathematical background of an hypothetical martian jet-pack design.

1 Introduction

The exploration of Mars is now a priority to NASA. During the first phases of human settlement in Mars, the astronauts will need to do a lot of activities outside of the habitats, including scientific, building and maintenance missions.

At this point, is where a jet-pack could be extremely advantageous. The development of this system will enable the astronaut to explore Mars as never has been done. The jet-pack allow the pilot to overcome obstacles such as mountains and rocks. Moreover, it permits the explorer to travel at higher speeds. The rocket engine proposed in this work burns liquid methane with liquid oxygen, as they are easily produced using on-site resources. An exoskeleton is used to reduce the weight burden in the astronaut, improving its force.

The modules needed to assembly the jet-pack and the different facilities needed to produce the propellant can be sent from Earth, but later developments might enable to build them directly from Mars resources.

2 Propellant production

As CO_2 is extremely abundant in the Mars atmosphere, the Sabatier reaction is a clear candidate for producing methane fuel for the jet-pack. In this reaction, CO_2 is mixed with H_2 in a reactor, producing CH_4, water and heat:

$$CO_2 + CH_4 \rightarrow CH_4 + 2H_2O - 165\,\mathrm{kJ\,mol^{-1}} \quad (1)$$

Water can be recycled and electrolized to produce hydrogen and oxygen:

$$H_2O + 286\,\mathrm{kJ\,mol^{-1}} \rightarrow H_2 + \frac{1}{2}O_2 \quad (2)$$

The waste heat of the Sabatier reaction can be used to heat up the electrolysis reactor, so its energy consumption can be reduced. In order to produce one mol of CH_4, 2 mol of H_2O have to be extracted from the ground. The water extraction can be easily performed if the soil contains high amounts of ice: ground fragments can be put into contact with pressurized atmosphere at moderate temperatures, so the water ice melts instead of sublimating, producing liquid water. Hydrogen trapped in rocks can be extracted using supercritical CO_2, trapping C in the ground and producing water. Using data from [1], a methanator producing 10 kg of propellant per day has an estimated weight of around 500 kg.

The energy budget for the methanator is estimated using a heat transfer efficiency of 60 %, an electrolysis efficiency of 60 %,

typical solar cell efficiency as in the Opportunity Rover and assuming that an astronaut cleans the cells from dust [2, 3]. In this case, $692\,\mathrm{W\,h\,m^{-2}}$ are produced per sol, and 10.5 kWh are needed per kg of propellant, leading to slightly more than $150\,\mathrm{m^2}$ to produce 10 kg of propellant per sol. Typical monocrystalline and polycrystalline solar panels weight between $10\,\mathrm{kg\,m^{-2}}$ and $20\,\mathrm{kg\,m^{-2}}$, so between 150 kg and 300 kg will be needed. The modular nature of solar arrays ensures that they can be easily disassembled, transported and reassembled if they are needed elsewhere. Other options could be also used, such as a small nuclear reactor transported by a light truck, but the solar panels reduce the mission risks and are more easily replaceable.

This solution differs from other such as the ones proposed in [**mars_direct**] in that, instead of using H_2 sent from Earth, it uses only resources from Mars.

3 Mars region selection

Comparing different regions of Mars by studying different maps of Mars' relief, the composition of the soil in Mars, the percentage of hydrogen in the first meter of Mars's soil and the location of Mars' equator, we have decided to perform our mission in the region called 'Arabia Terra'.

'Arabia Terra' is a region that is located at 0 longitude and just above the equator, what we where looking for. As we can see in the upper part of Figure 1, the relief in the selected region is almost plane and constant over all the surface. Also, the reduced height ensures a relatively high atmospheric pressure, so it can be more easily used. Taking a look at the bottom part of Figure 1, the percentage of Hydrogen concentration in this region is high enough to ensure a supply of H_2 for the duration of the mission. This figures have been produced by modifying the works from [4] and [5].

The height varies from −4000 mweight solar panel to 1000 m above the mean Mars surface level. In

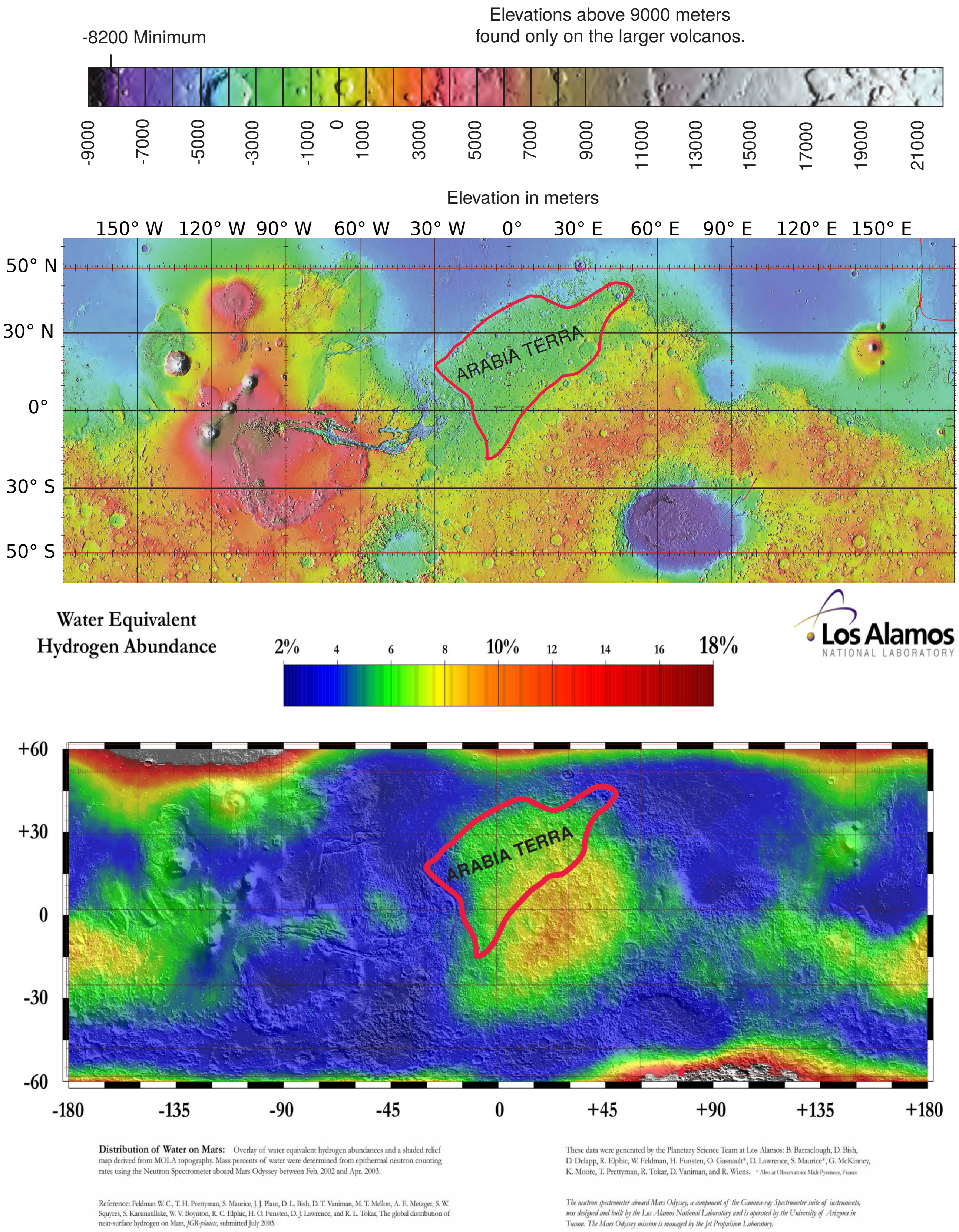


Figure 1: Settlement location in Arabia Terra. The figures are modified versions of [4] and [5]

these conditions, the atmospheric pressure varies from 1001 Pa to 639 Pa, whereas the density ranges from $0.0212\,\mathrm{kg\,m^{-3}}$ to $0.0138\,\mathrm{kg\,m^{-3}}$. Although bigger pressures ensures better collection of atmospheric gases, it also reduces the operating range of the jet-pack as the density increases, as will be shown later.

4 Propellant needs

In this section we are going to calculate the amount of propellant needed to finish the mission safely. This amount is going to variate proportionally to the travel time and type of the mission, meaning that if we travel more time we will need more propellant and if we have a more 'aggressive' mission such as climbing mountains or traveling at higher speed we will also need more propellant.

The first stage of the problem is to enumerate the different masses of the system and its approximate estimation value. For this system we have:

- m_a: Astronaut mass (from 50 kg to 90 kg)
- m_e: Exoskeleton mass (20 kg)
- m_s: Suit mass (55 kg)
- m_{ls}: Life Support System mass (10 kg)
- m_{es}: Electric System mass (1 kg)
- $m_{\mathrm{CO_2}}$: Carbon dioxide mass (variable, depends on the propellant mass).
- m_{jp}: Jet-pack mass (30 kg)
- m_p: Propellant mass (from 50 kg to 200 kg)
- m_d: Dry mass, as a sum of all the masses except the propellant mass.

The rocket thrust F is equal to the total weight during fixed point flight:

$$F = Isp \cdot \dot{m}_p = \left(m_d + m_p\right) \cdot g \tag{3}$$

where Isp is the specific impulse of the rocket engine and $\dot{m}_p$ is the propellant mass flow rate. This specific impulse has been computed for different altitudes, from −4000 m to 1000 m, and for a combustion chamber pressure going from 10 MPa to 50 MPa. Figure 2 shows the results for the specific impulse computed using CEA [6]. The specific impulse seems to be bigger than $3000\,\mathrm{m\,s^{-1}}$ until the combustion chamber pressure drops to values close to 10 MPa. Also, its value starts to decrease in a dramatic way as this pressure becomes smaller, so a minimum combustion chamber pressure of 10 MPa will be imposed.

Figure 3 shows the jet outlet temperature at different altitudes and combustion chamber pressures. The values are relatively cold, reducing the risk for the astronaut. The combustion chamber temperature ranges from 1290 K to 1440 K, so the walls will be cooled down using the liquid oxidant and fuel.

CO_2 is needed to pressurize the fuel and oxidizer, and is a function of the total mass of them. This mass will be set as the one needed to keep the combustion chamber pressure bigger than 10 MPa. To reduce the performance reduction due to CO_2 diffusion in the fuel or the oxidant, a piston should be used. Results for the mass of $COtwo$ needed are shown in Figure 5: around of one third of the propellant mass will be needed in $COtwo$ mass for pressurization. Also, a turbopump might be used for pressurization instead of CO_2: it has the advantage of a smaller weight, but it is more complex and complicated to maintain.

In this fixed-point flight mission, the jet-pack endurance is:

$$\Delta t = -\int_{m_{p0}}^{0} \frac{Isp\,\mathrm{d}m_p}{g \cdot \left(m_d + m_p\right)} = \ln \frac{m_d + m_p}{m_d} \tag{4}$$

Figure 4a shows the jet pack operating time for propellant masses ranging from 50 kg to 200 kg and astronaut masses from 50 kg to 90 kg, using CO_2 for pressurization. Figure 4a shows the same information, using a turbopump of 10 kg. A propellant mass of 100 kg ensures more than 300 s of operation in either case for the whole range of astronaut mass. A propellant mass of 100 kg and a CO_2 pressurization system is selected to reduce the complexity of the system. The total mass is around 350 kg and, even in the reduced gravity of Mars' surface, this produces a weight equivalent to that of 132 kg in Earth. Even more, the total momentum is big enough to produce a lot of problems for the astronaut to move around freely. An exoskeleton is added to reduce these problems, increasing the astronaut's force. The exoskeleton introduces also an extra layer of protection against physical accidents, increasing the safety of the mission.

5 Maximum horizontal range

In the following figures, the maximum horizontal range for jet-pack operation is shown. In this case, the total thrust $Isp \cdot \dot{m}_p$ when the steady-state speed is reached is:

$$Isp \cdot \dot{m}_p = \sqrt{\left(\frac{1}{2} \cdot \rho \cdot v^2 \cdot A_f \cdot C_D\right)^2 + \left[\left(m_d + m_p\right) \cdot g\right]^2} \tag{5}$$

where A_f is the frontal area, equal to around $2\,\mathrm{m^2}$, C_D is the drag coefficient, equal to 1.3, and v is the flow speed.

The flight endurance is:

$$t = \left. \frac{2 \cdot Isp \cdot \tan^{-1} \frac{8 \cdot g^2 \cdot m_p + 8 \cdot g^2 \cdot m_d}{4 \cdot A_f \cdot C_D \cdot g \cdot \rho \cdot v^2}}{A_f \cdot C_D \cdot g \cdot \rho \cdot v^2} \right|_{m_{p0}}^{m_{p1}} \tag{6}$$

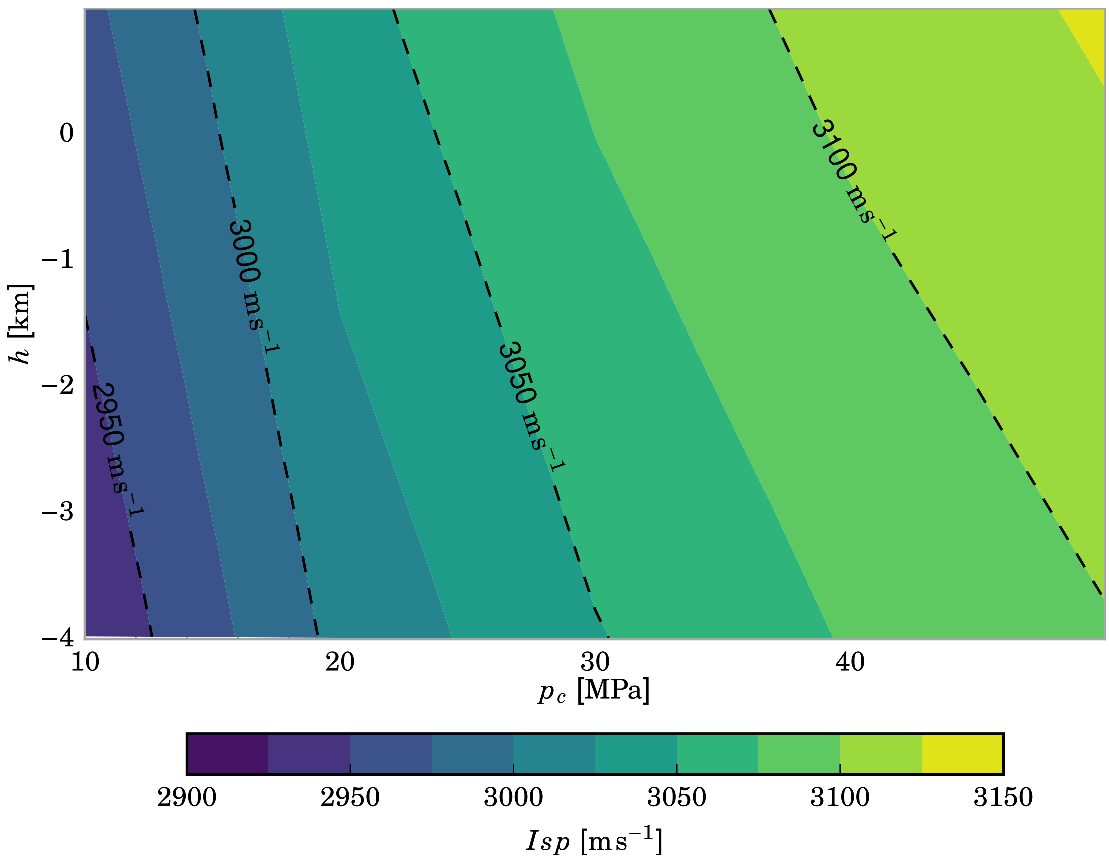


Figure 2: Specific impulse for different combustion chamber and ambient pressures

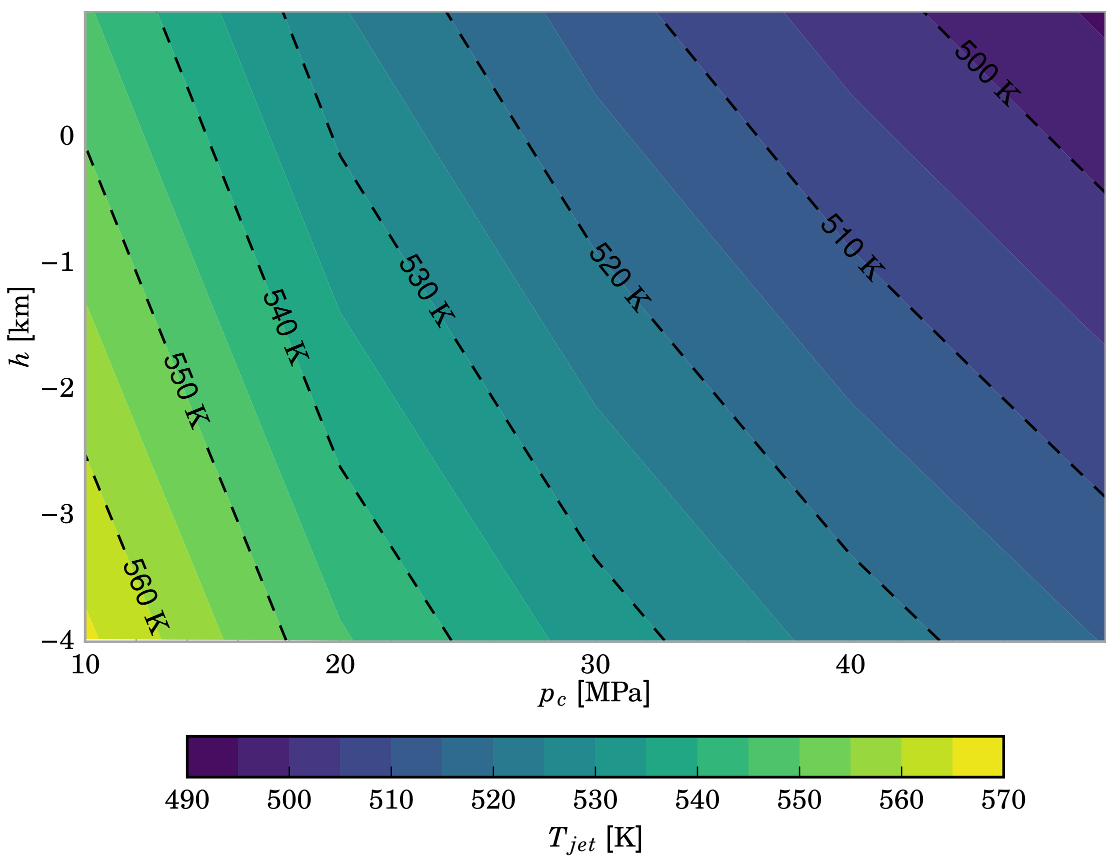
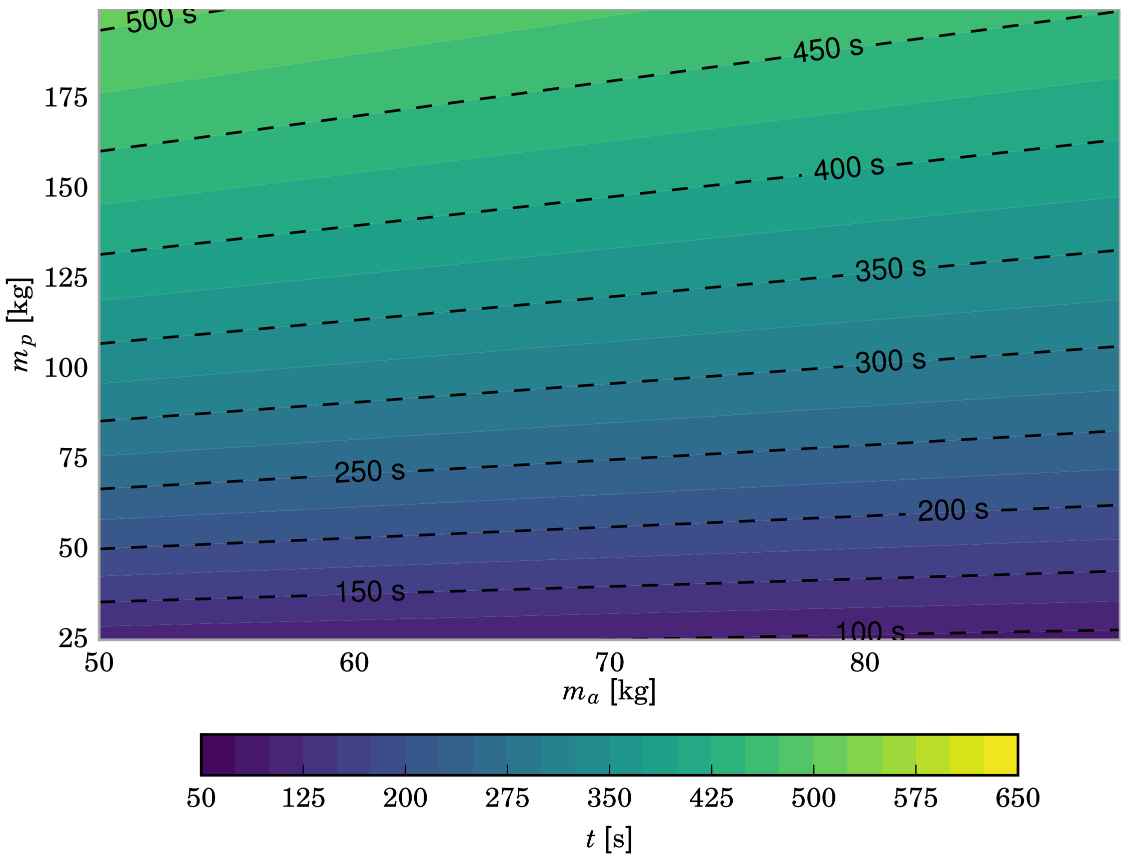
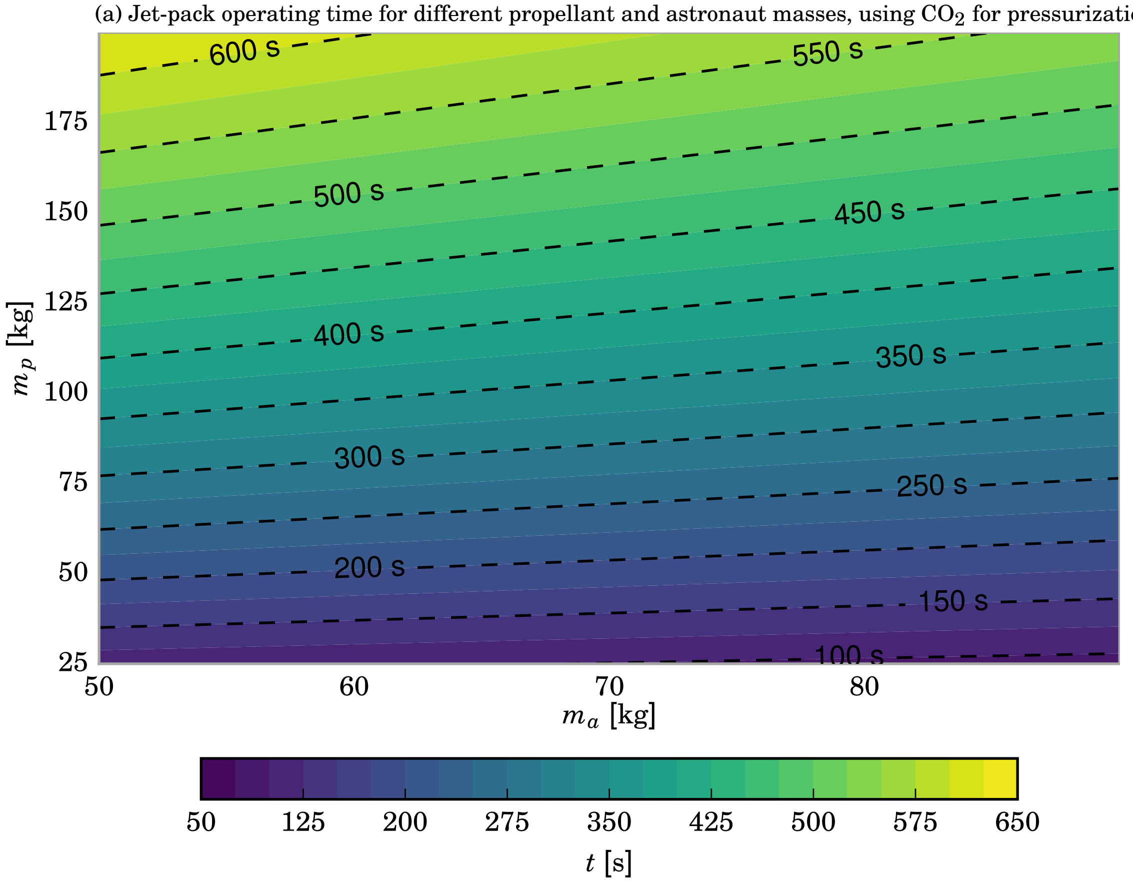


Figure 3: Specific impulse for different combustion chamber and ambient pressures



(a) Jet-pack operating time for different propellant and astronaut masses, using CO_2 for pressurization.



(b) Jet-pack operating time for different propellant and astronaut masses, using a turbopump for pressurization.

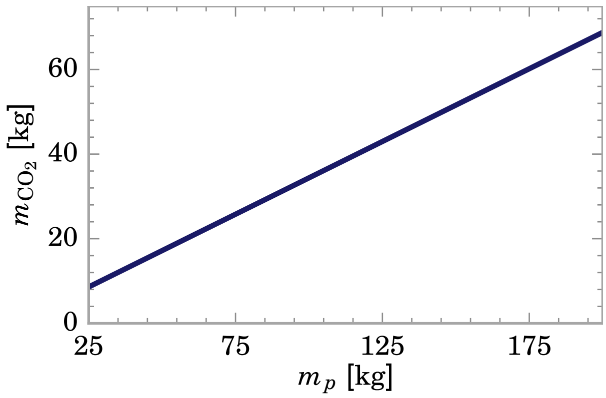


Figure 5: CO_2 mass needed for pressurization as a function of the propellant mass

where m_{p0} is the initial propellant mass, equal to 95 kg, and m_{p1} is the final propellant mass, equal to 5 kg. Around 10 kg of propellant are not used during this steady-state phase: it will be used for take-off, acceleration, deceleration and landing. The range is, thus:

$$L = t \cdot v \tag{7}$$

Figure 6a shows the mission range for a 60 kg astronaut, whereas Figure 6b shows the same information for a 90 kg astronaut. The figures show optimum speeds for different altitudes: this optimum speed grows with rising altitudes and ranges between $175\,\mathrm{m\,s^{-1}}$ to slightly more than $210\,\mathrm{m\,s^{-1}}$. The maximum range is obtained for the maximum altitude, being more than 35 km. When using a propellant mass of 25 kg, the range is greatly reduced, but is still enough for more than 6.5 km missions, as shown in Figure 7a and Figure 7b.

6 Jet-pack architecture

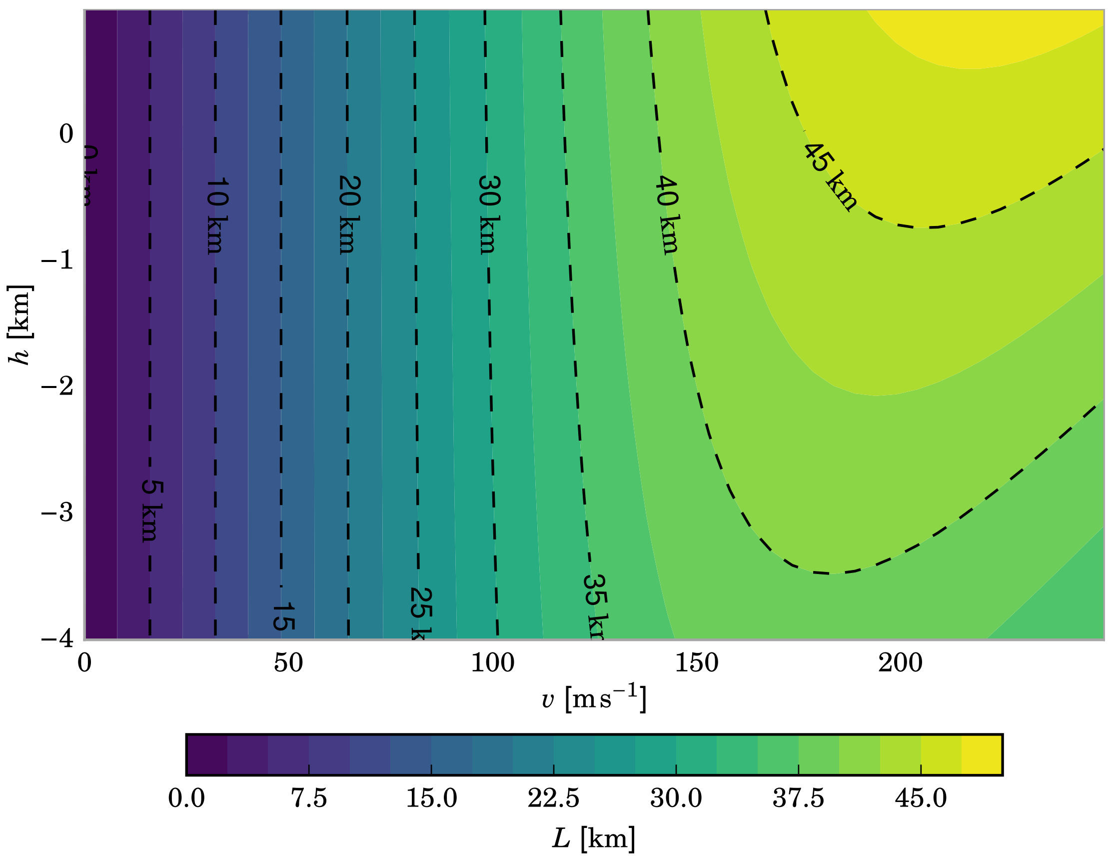
Having discussed the feasibility of the system it is necessary to tackle its physical layout. It has been decided to design the jet-pack so the bulk of the astronaut mass and propellant mass swings below the propulsion nozzles. This way, the natural stability of the system means that no active control is needed on this axis. Several designs were studied and it was concluded that the one that minimizes weight while keeping the system safe and controllable is a twin nozzle configuration side to side across the user's shoulders. A pair of actuated gimbaled nozzles is going to be mounted on a foldable cross member. When the system is unused it can be retracted on the back of the wearer, re-opening again when needed. A specific mechanical hinge will ensure that the open position is the one of maximum strength by limiting the range of movement of the aforementioned hinge. The gimballing action of the nozzles provides active yaw, lateral, longitudinal and translation control capabilities. The actuators for this system will be electromechanical in order to keep a low weight figure. Roll and pitch control are passively stable due to the configuration elected and, since the martian atmosphere is very thin, there is no important impact on flight performance due to poor aerodynamic astronaut flying position. Also, it is desirable to use aerospike type nozzles to accommodate for change in pressure conditions while using the jet-pack on different scenarios and maximize the specific impulse of the rocket engines while keeping the weight low efficiently. Figure 8 shows a concept for the jet-pack physical appearance together with the exoskeleton.

7 Exoskeleton description

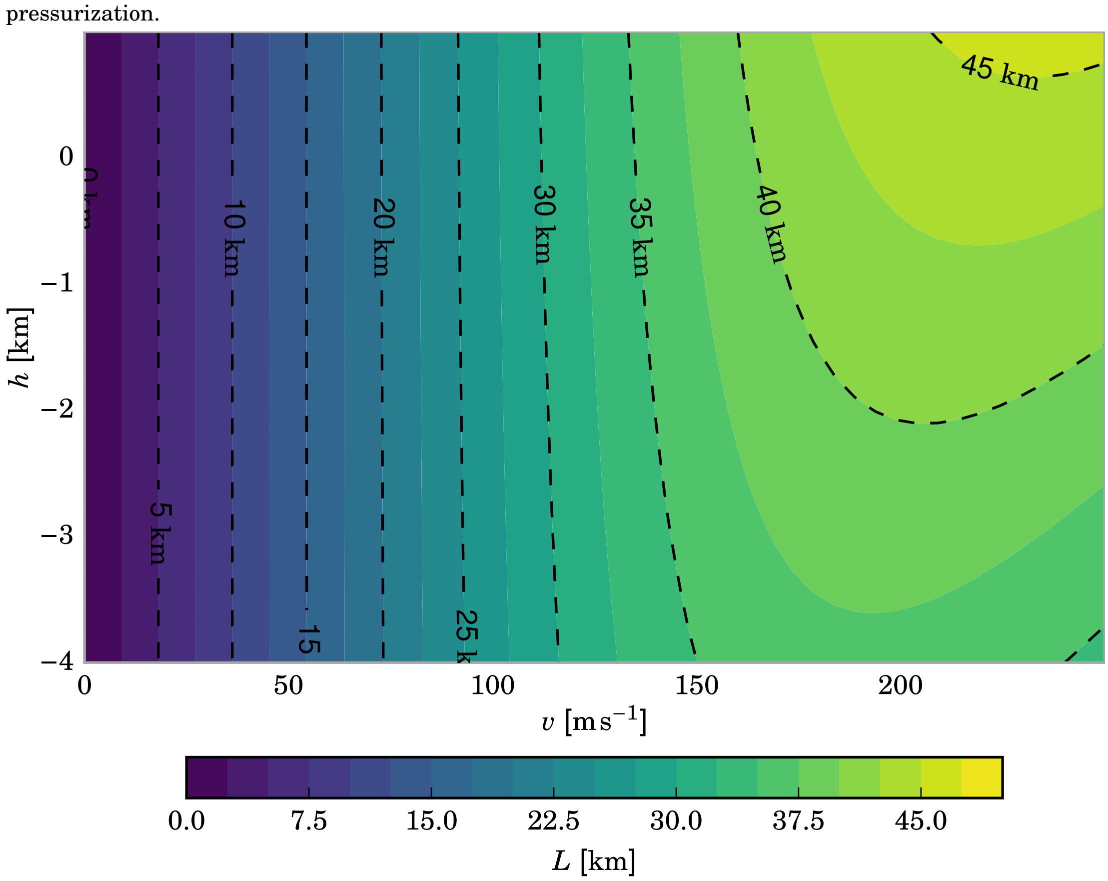
As it has been described along this work, the astronaut will be carrying over three times its mass during the development of an EVA. Despite the martian gravity is roughly a third of Earth's, the inertia of this increased mass means that the stability of the astronaut and its dexterity performing tasks will me diminished. To avoid potentially dangerous situations, muscular fatigue and to increase the versatility of the mission, the proposed transport solutions relies on the use of an exoskeleton.

This exoskeleton shall be worn on top of a EVA suit and it should be able to be removed and equipped by a single astronaut. This can be accomplished if the suit is setup as a chair (in a metaphorical sense) that embraces its carrier. The suit will augment the force and dexterity of the user via electromyographic sensing and positive feedback on intelligent polymer fabrics and actuators. These polymers will contract and relax through current applications, imitating the natural muscle workings. Fully sensored, it will be able to monitor the user's overall health status, report medical conditions to the mothership and it could even serve as a resuscitation aid should a cardiac arrest occur. Also, it could provide aid in the rehabilitation of lesions and ease the transport of injured personnel through immobilization of the patient or its injured member, joint or zone.

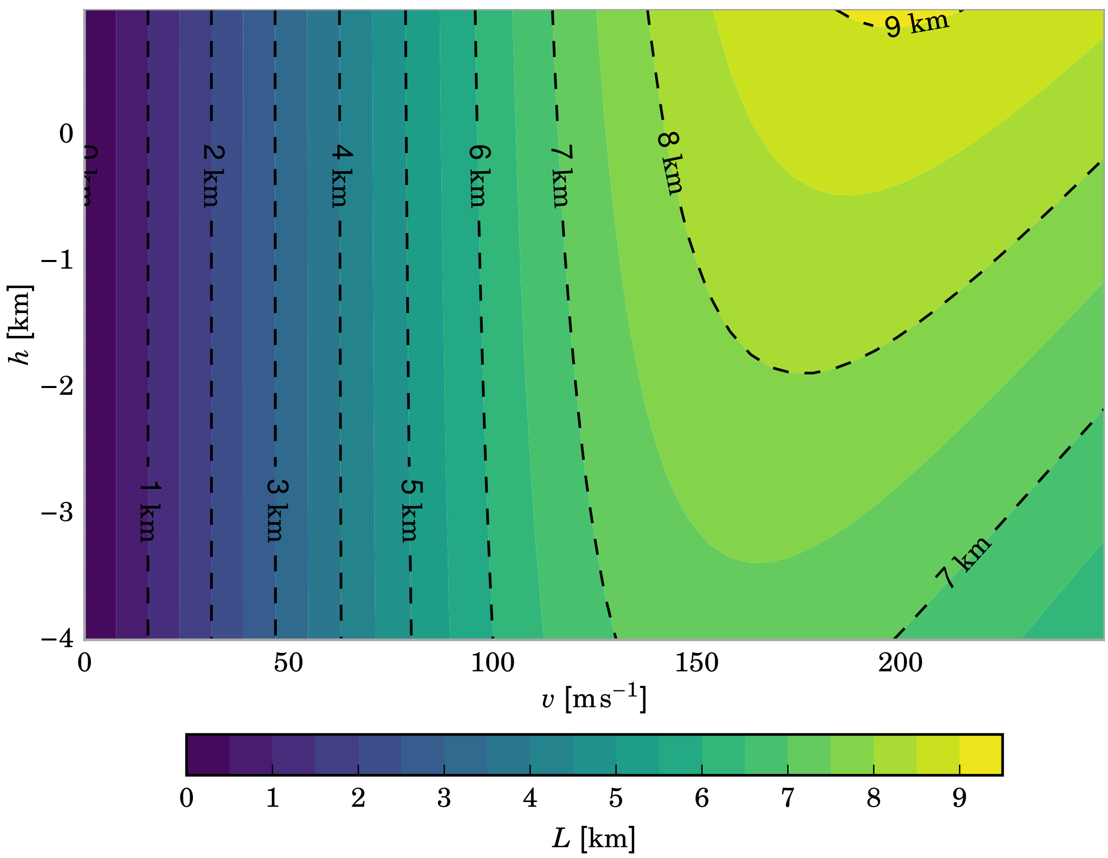
The field of intelligent polymers and fabrics has experienced a steady growth in the last decade. Today, many materials are capable of altering their mechanical, optical, electrical and surface properties in response to different stimuli. These materials range from electric field sensitive fabrics to magnetic field dependent composites and fluids. The proposed exoskeleton would make use of these technologies in order to provide both support and strength to the wearer. With the current technology, this system would allow a regular astronaut, which would have lost an important part of his muscle due to microgravity during the travel, to perform tasks safely and effectively, maximizing the travel's scientific throughput.



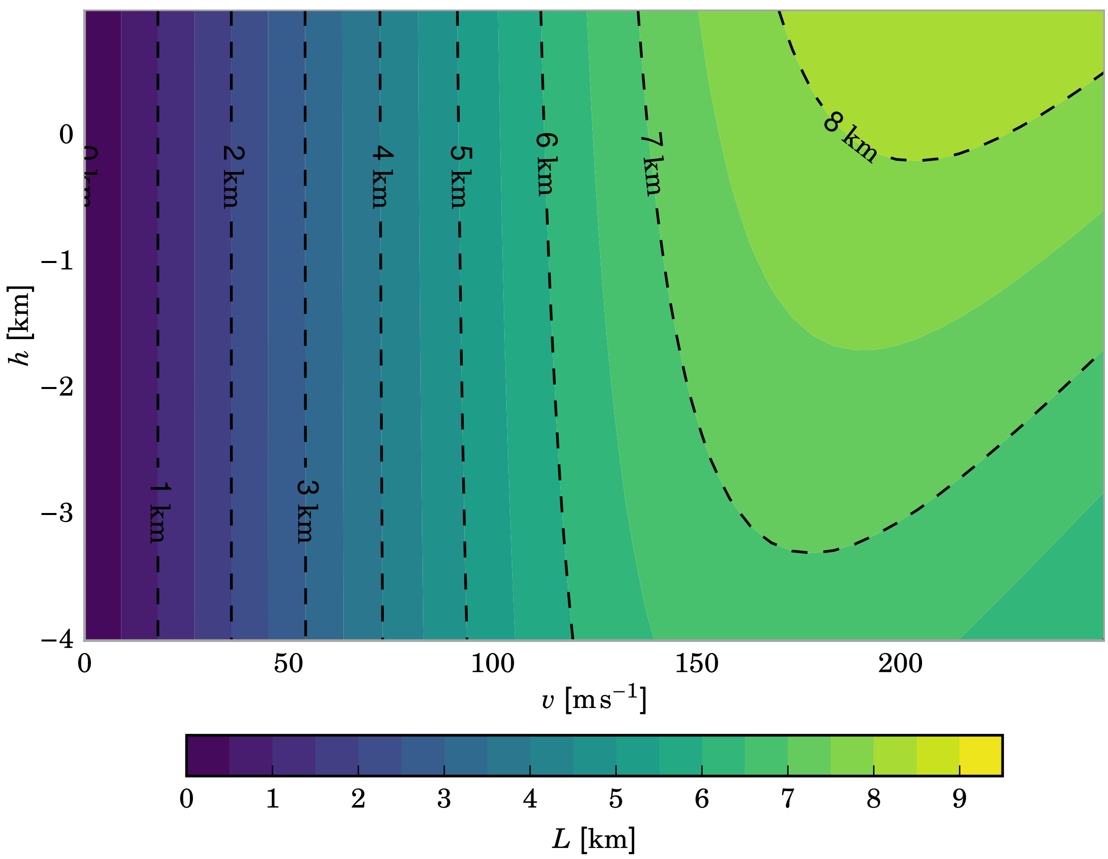
(a) Jet-pack endurance at different altitudes and speeds, for an astronaut mass of 60 kg, 100 kg of propellant and using CO_2 for pressurization.



(b) Jet-pack endurance at different altitudes and speeds, for an astronaut mass of 90 kg, 100 kg of propellant and using CO_2 for pressurization.



(a) Jet-pack endurance at different altitudes and speeds, for an astronaut mass of 60 kg, 25 kg of propellant and using CO_2 for pressurization.



(b) Jet-pack endurance at different altitudes and speeds, for an astronaut mass of 90 kg, 25 kg of propellant and using CO_2 for pressurization.

8 Augmented reality system

The transport solution here developed entitles not only the jet-pack and the exo-suit, but a complex augmented reality HUD helmet and system. The user of the suit will have available a customizable selection of several parameters of the environment and its suit. This information will be presented through an immersive Heads-Up-Display that will react and learn with the user, a concept for the helmet is shown in figure Figure 9. The data captured by the sensors of the suit will be processed and relayed to other astronauts and the exploration base for further analysis. Additionally, our design incorporates a bracelet which can be used to monitor key health parameters and the status of the suit's systems. This is not just used for the visualization of the main user, but also for other astronauts to aid in case of depressurization, accident or other kinds of dangerous situations.

9 Connectivity and systems integration

The suit's systems will interact together with the jet-pack controls and processing units. It is key to provide advanced functionality besides the basic flight capability. A selection of different selected features would be:

- Health monitoring: As mentioned, the suit will interact with the user and it will be able to measure key vital parameters and other information such as load bearing on joints and limbs or provide an interface with the user's brain functions via non-intrusive electroencephalography or other kinds of BMIs. Eye-tracking technology will be incorporated so the user can aid the exploration of the environment by the suit's sensor set.

- Navigation: It is key to the augmented reality system to be able to show real-world and real-time information about the topography, relief, distance, composition and any other relevant known fact of the terrain to the user. This function together with the ability to enable users to mark key waypoints and information would enable fast and responsive exploration events.

- Threat alert: Weather forecasting and potentially dangerous terrain alerts shall be part of a threat alert system for the HUD.

- Automatic flight: Despite it will be piloted normally for flights, it is possible to include autonomous flight capabilities to the system. This would allow the user to demand a suit in certain situations and it would be able to fly towards the user or return to the base for autonomous recharging.

- Terrain recognition: It is interesting to obtain high resolution martian scanning data while the jet-pack is flying. It provides an opportunity to mount a stereoscopic camera to t and perform these scans on-the-fly.

10 Mission concept

This development, although very interesting from the perspective of Mars exploration, would require a mass budget that makes it difficult for being included on a crewed mission, specially the fuel processing equipment. To aid with this, a sequential mission is proposed. Firstly, a set of supply missions would be launched from the Earth during a Mars transfer window. These missions would transport the habitat for the explorers as well as supplies for the mission and an RTG-powered robotic fuel processing factory. This factory would have arrived to the planet with sufficient time in order to process the required amounts of products in order to generate the fuel, not just for the jet-pack, but possibly for enabling the return vehicle to carry a greater payload back to Earth. As the factory would slowly produce methane and oxygen from the martian soil and atmosphere it will also extract other components such as surplus water for the mission, Argon, Carbon dioxide, pure Carbon, Magnesium, Aluminum, Silicon, Phosphorus, Chlorine, Sulfur, Calcium, Titanium, Iron and other metal amounts. Using these, a set of replicating factories could be built and an expanding robot based exploration could be started, easing future exploration and colonies. Further power needs will be supplied with later solar panel upgrades.

11 Conclusions

A LOX + CH_4 powered jet-pack is proposed to ease early human settlements on Mars. This jet-pack can be used as a mobility solution, enabling the astronauts to fly over obstacles and to move fast between different outposts.

100 kg of propellant ensures more than 300 s of fixed-point operation and more than 35 km of horizontal range at high speeds. The production of the propellant can be easily done using water from the ground and atmospheric CO_2 and a moderate surface of solar cells for producing electrical energy.

An exoskeleton is also used to increase the astronaut's force, as the total mass of the system plus astronaut can be around 350 kg when fully loaded with fuel. The exoskeleton is even interesting as an extra layer of protection against physical harm and can provide extra functionality.

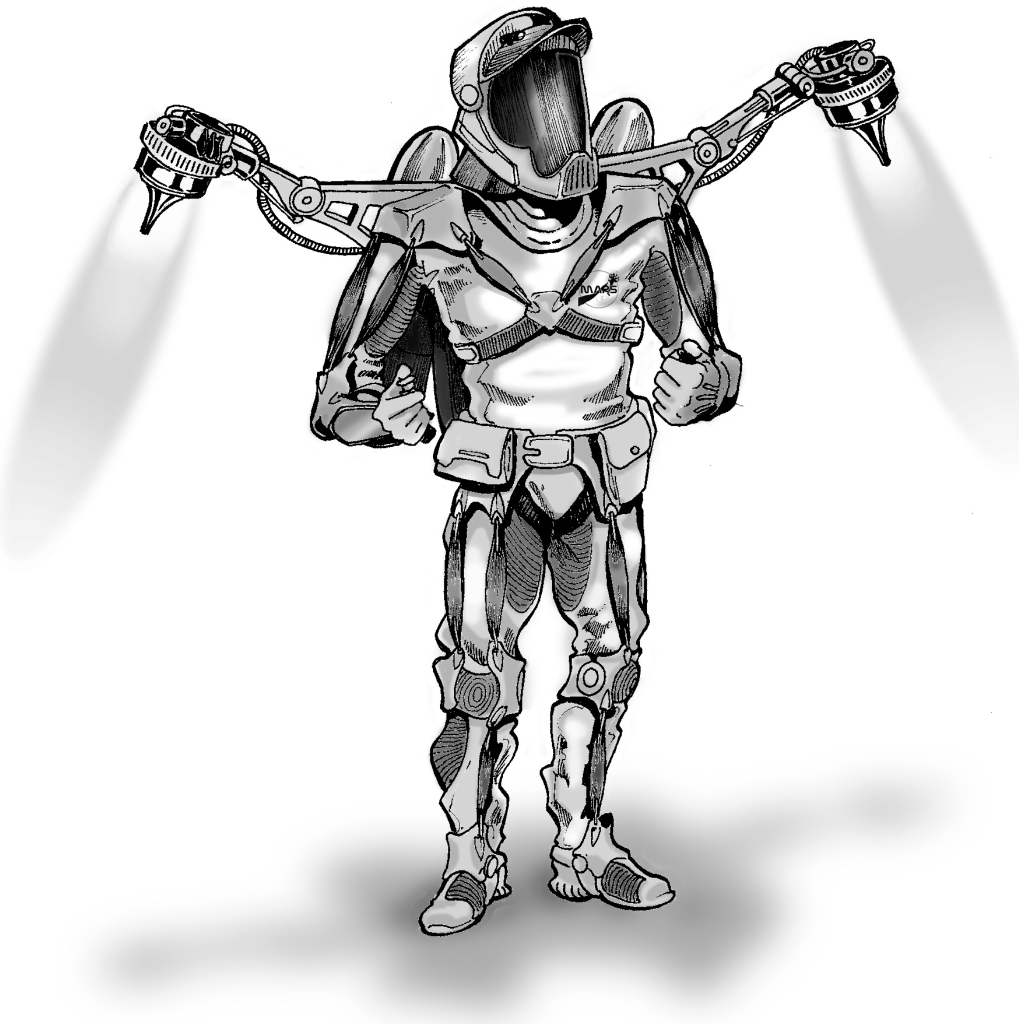


Figure 8: Jet-pack concept art.

Figure 9: HUD helmet concept art.

List of symbols

Symbol	Description
A_f	Frontal area
C_D	Drag coefficient
F	Thrust
g	Acceleration of gravity
h	Altitude
Isp	Specific impulse
L	Range
LOX	Liquid oxygen
m_a	Astronaut mass
$m_{\mathrm{CO_2}}$	Mass of CO_2
m_d	Dry mass
m_e	Exoskeleton mass
m_{es}	Electric system mass
m_{jp}	Jet-pack mass
m_{ls}	Life support mass
m_p	Mass of propellant
m_s	Suit mass
$\dot{m}_p$	Propellant mass flow
ρ	Atmospheric density
t	Time
T	Temperature
v	Flight speed

References

[1] Robert M. Zubrin and Berggren Muscatello. "Integrated Mars In Situ Propellant Production System". In: *Journal of Aerospace Engineering* 26 (2013), pp. 43–56. DOI: 10.1061/(asce)as.1943-5525.0000201.

[2] NASA. *Opportunity Updates*. URL: http://mars.nasa.gov/mer/mission/status_opportunityAll.html (visited on 04/23/2016).

[3] NASA. *Mars Exploration Rover Launch*. June 2003.

[4] USGS Astrogeology Science Center. *MOLA global image showing boundaries of regional feature names*. URL: http://planetarynames.wr.usgs.gov/images/mola_regional_boundaries.pdf.

[5] Los Alamos National Laboratory/JPL. *Distribution of Water on Mars*. URL: http://mars.jpl.nasa.gov/odyssey/gallery/latestimages/20030724a.html.

[6] NASA Glenn Research Center. *Chemical Equilibrium with Applications*. URL: http://www.grc.nasa.gov/WWW/CEAWeb/ceaHome.htm.