Human System Interactions in the Design of an Interplanetary Mission

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Abstract

It has been suggested that the design of the last NASA reference mission for the human exploration of Mars is lacking sufficient considerations for human factors and human machine interactions. The NASA team examined many different options, long or short stay, chemical or nuclear thermal propulsion, pre-deploy or all-up, in situ resource utilization (ISRU) or not, etc. The decision process was based on a bottom-up approach, which led to local optimizations but to unpractical solutions in certain domains. For instance, the optimal number of astronauts has been determined according to skills requirements and organizational issues but no attention has been paid to its impact on the payload, on the mass of the landers, on the volume of the habitat and on the overall risks of the mission. A human centered design approach is proposed here, with a particular focus on interdependencies and human systems interactions. Following the guiding principles of human rated space systems, it is suggested that different choices may be more appropriate. The main ones are a reduction of the size of the crew, the entire duplication of the mission and a trade-off between "pre-deploy" and "all-up".

Introduction

In the 2009 NASA report describing the reference scenario for a human mission to Mars, it is stated (Drake, et al., 2009): “The general story that was constantly reiterated from the individual mission risk analyses was that current design philosophies and technologies would not provide an acceptable level of reliability for a Mars mission.” This statement is rather pessimistic. However, recently it has been suggested that human systems interactions (HSI) have not been carefully examined (Salotti, 2011, Salotti & Claverie 2012). This is somewhat surprising because human centred design and HSI are considered key issues in NASA certifications of human rated systems (Maguire, 2001, O'Connor, 2011, Boy, 2012). Theoretically, two important principles have to be followed:

a) The reduction of the risks by the tolerance to multiple failures and a high number of backup strategies.
b) Humans (astronauts) must have the possibility to take manual control on the systems and to obtain all relevant information on the state of the vehicle.

In D. de Waard, K. Brookhuis, F. Dehais, C. Weikert, S. Röttger, D. Manzey, S. Biede, F. Reuzeau, and P. Terrier (Eds.) (2012). Human Factors: a view from an integrative perspective. Proceedings HFES Europe Chapter Conference Toulouse. ISBN 978-0-945289-44-9. Available from http://hfes-europe.org

Did the NASA team follow these principles in their design of the reference mission? The question is addressed in the paper. In the next section, an overview of the mission is presented and the decision making process is discussed, with a specific focus on human systems interactions. In the following section, principles a) and b) are taken into consideration and suggest other options, which lead to another scenario that would probably be less risky and less expensive than the NASA one.

NASA reference mission

Problematic

Before addressing methodological issues, it is important to understand the problematic of human missions to Mars. It takes about two years for Mars to complete a single orbit around the sun. In order to benefit from the velocity of the Earth rotating around the sun (30 km/s), specific planetary configurations have to be awaited before sending a rocket to that planet and it takes between eight to ten months to reach it (Hohmann Transfer). Then, in most realistic scenarios, the astronauts have to stay five hundred days on the surface of Mars before the next appropriate planetary configuration occurs and the inbound trip can be undertaken. A human mission to Mars is very complex. NASA teams have been working on the subject for decades (Portree, 2001). The first "reference mission" has been published in 1997 and several updates have been released, the last one in 2009 (Hoffman & Kaplan 1997, Drake, et al., 1998, Drake, et al., 2009). There is one major difficulty that has to be overcome in the design of such a mission. It is the total payload mass that has to be sent to Mars. Even if a huge launcher is built, many launches will be required and a long and complex low Earth orbit (LEO) assembly will perhaps be unavoidable. The risks and the costs are tightly coupled to the complexity of the mission and therefore to the total payload mass. For that reason, specialists of the domain often focus on technological solutions for its reduction. For example, the NASA team suggests the use of nuclear thermal propulsion that could theoretically allow significant mass savings. Moreover, in order to avoid the landing of huge amounts of propellant for the launch of the Mars ascent vehicle at the end of the stay, it is recommended to produce propellant using Martian resources. If insufficient efforts are provided to reduce the overall mass that has to be sent to Mass, the mission becomes dramatically complex and unrealistic. Thus, the focus on technological solutions is clearly justified. However, such efforts should not be undertaken at the expense of the methodology and the consideration of other important parameters and especially human factors and human systems interactions.

The crew

In the first NASA reference mission, the problem of the composition of the crew has been addressed (Hoffman & Kaplan 1997). The question is what the most appropriate number of astronauts for a mission to Mars is. In the literature, different numbers can be found, typically between three and twelve (Portree, 2001, Salotti, 2011). For the reference mission, specialists of human factors and knowledge management have worked on the problem. They took into consideration the objectives and needs of the mission, the functions that had to be fulfilled by the astronauts at different stages, the necessity of redundancy of the skills, organizational issues and they finally made a proposal. The best crew size is six. It is not imperative but recommended as a good trade-off. The arguments have been presented in the 1997 NASA report and from that time on all NASA reference missions were based on a crew of six. Surprisingly, though it is mentioned in these reports that the number of astronauts might have a significant impact on the total mass that has to be sent to Mass, there has been no study on the subject. Obviously, there is an impact on many systems: consumables, accommodations, habitable volume, propellant amounts and perhaps on the organization and architecture of the mission, including human systems interactions. If the variability of such an important parameter has not been considered, are there other choices and another scenario that would outperform the current NASA reference mission?

NASA methodology

In order to determine the reference mission, the NASA team tried to adopt a methodological approach. However, the problems being very hard, it was decided to build a trade-tree. Key choices have been identified and represent the nodes of the trade-tree. A scenario is typically defined by a branch of the tree. Here are the key choices:

- Conjunction class mission / Opposition class mission: Briefly, the first choice minimizes the amount of propellant required for the transfer between the Earth and Mars, while the second minimizes the time spent on Mars. The first option is preferred by most specialists because it allows important mass savings.
- Pre-deploy / all-up: The first choice consists in the pre-deployment of assets on the surface of Mars before sending the manned vehicle. If the second choice is preferred, all space vehicles are sent to Mars at the same time. The pre-deploy option is often preferred because the Mars ascent vehicle is refueled and ready to take off before any human is sent to Mars. This choice is further discussed in the next sections of the paper.
- Aerocapture / propulsive: A space vehicle entering the neighbourhood of Mars must reduce its velocity to reach a Martian orbit. There are two options. The first is to use a propulsion system and to consume large amounts of propellant. The second is to follow an accurate trajectory that goes through the upper layers of the Martian atmosphere for an aerobraking manoeuvre. Aerocapture, which optimizes aerobraking for Mars orbit insertion, is often chosen because it enables important mass savings but it is a difficult manoeuvre and a heavy heat shield has to be added to protect the space vehicle. The NASA team chose aerocapture for the two cargo vehicles but not for the manned vehicle.
- ISRU / no ISRU: In situ resource utilization (ISRU) is a key idea for the reduction of the mass that has to be landed on Mars. There are many different options for the ISRU choice. Methane plus oxygen are often chosen as the reactants that can be used as propellant for the Mars ascent vehicle. Both of them can be manufactured on Mars thanks to the presence of carbon dioxide in the atmosphere and water in the ground but numerous problems have to be solved. The NASA team examined all options and recommended to bring the methane from the Earth and a chemical unit that can extract oxygen from the

carbon dioxide of the Martian atmosphere. This choice is analyzed from the point of view of human systems interactions thereafter.

- Nuclear Thermal / Electric / Chemical: The choice of the propulsion system for the transfer between low Earth orbit and Mars is very important. Chemical propulsion is mastered since a long time. Nuclear thermal propulsion is more efficient: with the same mass of propellant, the velocity gain is higher. However, a small nuclear reactor has to be sent to Earth orbit and an assembly of the space vehicle is required. The use of electric propulsion systems is another option. Theoretically, it is more efficient than nuclear thermal propulsion, but a heavier nuclear reactor would be needed and the acceleration would be very low and at the expense of the travel time. The NASA team performed an analysis and the preferred choice was nuclear thermal propulsion.

The five nodes of the trade-tree have been investigated by NASA. Numerous comparisons have been performed and each option is discussed. However, the focus has been on technological issues. In the introduction of the paper, we presented the two main recommendations for human rated space systems, which relate to the redundancy of systems and their control by the astronauts. These principles have not been taken into account in the NASA study or in an insufficient way. Let us provide two examples:

- When the manned vehicle is sent to Mars, it is isolated. There is no backup vehicle (redundancy principle). If for any reason the habitable module becomes inhabitable or the propulsion system is out of order (as it was the case in the Apollo XIII mission), the crew is lost. The problem has been identified by NASA but there is neither analysis of the risks nor proposals to solve the problem.
- The use of robotic excavators has been examined for the process of water production, from which hydrogen can be extracted and used for the production of propellant (methane + oxygen). NASA conclusion is that there are too many uncertainties in the use of robotic excavators, which are supposed to operate automatically while astronauts are still on Earth ("pre-deploy" strategy). Surprisingly, despite the recommendation of providing maximum control on the systems to the astronauts, the possibility of a control of the work by the astronauts has not been examined. In the context of the "all-up" option, such a possibility should have been clearly identified.

The objective of this work is not to criticize the tremendous work that has been performed by the NASA team. NASA reference missions are described in several long reports with many technical details. The problems are very complex and the constraints are very strong. The analysis of a restricted number of options is unavoidable. NASA decided to fix the number of astronauts and to focus on technological issues without paying much attention to human systems interactions and interdependencies, at least in the analysis of the different choices of the trade-tree. This is a reasonable choice but it is important to understand the lacks of the approach and to perform later on a complementary analysis that can bring another point of view and eventually suggest important changes for the architecture of the mission.

Human rated systems for human missions to Mars

Redundancy

A mission to Mars requires the control of many complex critical systems. The first ones are propulsions systems. In most cases, it is not possible to duplicate them in totality because the mass penalties would be too high. If the main engines fail or if there is a problem with the propellant, the risk of loosing the space vehicle and the crew is significant. Life support systems also are critical. There must be a total control on the quality of the air: pressure, temperature, resupply of oxygen, removal of carbon dioxide and water vapor, absence of nocive particles. If one of these systems does not work properly, the lives of the astronauts are in danger. The water recycling process also is very important. If it fails, there would not be enough water to sustain the lives of all astronauts for the round trip. In order to reduce the risks of loosing the crew, robust systems will have to be chosen and carefully tested. However, this is not sufficient. A fundamental principle in the design of human rated systems is to consider the eventuality of their failures and to look for solutions to reduce the severity of their impact. Systems can be duplicated, tripled or quadrupled but there still exists a risk of multiple failures. An accident can also occur and destroy an important part of the vehicle, leaving only a few hours or days for a reparation or a rescue. In order to avoid the loss of the crew, such problems have to be anticipated and back-up strategies have to be developed. For the launch, the back-up strategy is well-known and adopted by all space agencies. A small top-mounted rocket is connected to the capsule. If there is a problem during the launch, the engines of the small rocket are fired and the capsule and its astronauts are quickly ejected a few hundred metres away. For the life support systems, the strategy is more complex. The NASA team suggests bringing numerous spare parts, tools for reparation and enough consumables for one month in open loop (no recycling). This might not be sufficient. Let us consider the Apollo XIII accident. An oxygen tank exploded and the command module was almost out of order. The astronauts survived thanks to the presence of the lunar exploration module, which provided life support and propulsion for the return to the Earth. In the context of the NASA reference mission for a journey to Mars, a similar accident during the transit between the two planets would cause the loss of the crew. The only way to solve the problem is to have another space vehicle closeby, which could dock to the former for transhipment of the crew. The same problem exists on the surface of Mars. If a habitat becomes unsafe or if a Mars ascent vehicle is not able to take off, an efficient back-up strategy consists in the duplication of the habitat and the Mars ascent vehicle. Remarkably, the entire duplication of the mission to Mars has already been suggested by one of the pioneer of the space conquest: Wernher Von Braun (Portree, 2001). His project was very ambitious with two crews of six and gigantic spaceships. The total payload mass was probably unrealistic. However, if the problem is the mass, there are two ways to overcome the difficulty. The first is to send only one spaceship, this is NASA approach. And the second is to reduce the size of the crew and to look for other solutions for other mass savings.

Size of the crew and impact on the systems

Obviously, the question of the best crew size in a single space vehicle is very different from the best crew size if the mission is entirely duplicated and if efforts are requested to reduce the mass that has to be sent to Mars. The main problem of allowing transhipment onto a second vehicle is that a single vehicle must be designed to sustain the life of twice the number of astronauts in the nominal situation. Does that mean, for example, that two vehicles with two astronauts in each and enough consumables for transhipment would be heavier than a single vehicle with seven astronauts and no transhipment? A detailed analysis has been performed. This intuitive idea is wrong for several reasons. First, transhipment must be considered the last option for the rescue of a crew. It is an emergency situation, which should rarely occur. If it occurs anyway, as it is the case in the navy, a reduction of the comfort is acceptable and the primary objective becomes the survival of all astronauts. Obviously, there should be enough consumables for all astronauts. However, there are at least three domains for which mass savings can be expected. The first is accomodations because they can easily be shared by the astronauts without impact on safety. The second is structure because a small habitable volume (for two crews) is also manageable. The third concerns the back-up strategies for life support systems. The number of spare parts and tools for reparation does not need to be slightly increased. In addition, the amount of back-up consumables, especially for open loop consumption, does not need to be doubled. Indeed, in most emergency situations, if there is time for rendezvous and docking, there is most probably time for transhipment of consumables together with the crew (and eventually accomodations). Let us consider another example with two astronauts and a capsule that has to be used the last day of the mission for the re-entry in the Earth atmosphere. In a normal situation, the two astronauts are in the capsule with two hundred kilograms of rocks that have been collected on the surface of Mars. In the context of an aborted mission due to transhipment during the transit between the two planets, there are four astronauts in the capsule and no rock at all. Therefore, the mass for Earth re-entry is roughly the same in both cases. As a consequence, the mass of two space vehicles with N astronauts in each and the possibility of transhipment is much less than twice the mass of a space vehicle with 2N astronauts.

Another important question is the minimum number of astronauts in each space vehicle. The problem has already been addressed (Kanasa, et al., 2009, Salotti, 2011). For evident safety issues, there must be at least two astronauts. Two is a very low number for a long mission but it is probably manageable if the crews are carefully selected and trained and if the two crews are always close the one another to provide an eventual help.

In situ resource utilization

In the NASA report, there is a detailed analysis of the possible solutions for the exploitation of local resources for the production of propellant. Assuming that the combination of methane and oxygen is the most appropriate propellant that can be manufactured on Mars, three main options are examined:

- Methane is brought from the Earth and oxygen only is produced on Mars.
- Liquid hydrogen is brought from the Earth and methane and oxygen are produced on Mars. This option allows more mass savings but it requires more energy and complex devices to store large amounts of liquid hydrogen during long periods of time. It was the recommended option for the 1998 NASA reference mission (Drake, et al., 1998). In the 2009 NASA study, however, the NASA team considered that the complexity of the solution was too high for a small benefit (Drake, et al., 2009).
- Nothing is brought from the Earth and methane and oxygen are manufactured on Mars. According to NASA, this solution allows the most significant reduction of the payload mass that has to be landed but as it was explained earlier here, it requires the complex use of robotic excavators.

There is no doubt of the feasibility of the last solution. The problem is the reliability of robots that have to be operated during several months. There are too many uncertainties due to robotic interactions with unknown environments. Robotic excavators can get jammed or damaged for many reasons. They can be extensively tested but there are numerous types of terrain and an almost infinite combination of difficulties. As it is almost impossible to prove the reliability of the systems, the NASA team rejected the solution. Nevertheless, an important question has not been addressed: if humans were present on the surface while the robotic excavators are working, would there be a significant improvement in the reliability of the systems? If a robot gets jammed between two rocks, an astronaut can easily free it. If a mechanism is broken, provided that spare parts and appropriate tools are available, it can be repaired. Last but not least, a back-up robotic excavator can also be stored in the space vehicle. This is typically a situation where humans can be considered technological enablers. Furthermore, "humans must have the possibility to take manual control on the systems". This simple recommendation for human rated space systems suggests that the presence of humans during the work of robots is an option that has to be seriously considered, especially if it allows significant mass savings. The NASA team performed a detailed comparison between the "pre-deploy" and "all-up" options, but the technologically enabling argument of the all-up case has been missed (Drake, et al. 2009, Salotti & Claverie 2012).

Conclusion

Following the guiding principles for the design of human rated space systems, it is suggested that other options deserve to be examined for a human mission to Mars. A reduction of the crew size to two astronauts and an entire duplication of the mission were the starting assumptions of another paper that was focused on technical issues for the design of an original scenario (Salotti, 2011). Moreover, a recent analysis of the risks for the entry, descent and landing on Mars suggests that the best solution would be to land with several small vehicles (mass less than thirty-three tons), which would be possible only if the size of the crew is less or equal to two astronauts (Salotti, 2012). In addition, such a solution avoids the needs for complex assemblies of different modules in low Earth orbit, thus reducing the complexity of the architecture of the mission. All in all, including the possibility of using robotic excavators if astronauts are present nearby, the proposed scenario seems much more simple and efficient than the NASA reference mission (Salotti, 2012). Therefore, the conclusion of this study is that designers of interplanetary missions should pay more attention to human factors and human systems interactions or they could miss the most promising solutions with possible impacts on the global architecture.

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