IAC-08-A5.1

OPEN INNOVATION FOR SPACE SYSTEMS – USING THE DEVELOPSPACE PLATFORM FOR DESIGNING A NEAR-TERM HUMAN MARS MISSION

Mr. Alar Kolk
Helsinki University of Technology (HUT), Finland
kolk@cc.hut.fi

Mr. Wilfried K. Hofstetter
Massachussets Institute of Technology (MIT), Cambridge, United States
wk_hof@mit.edu

Mr. Arthur N. Guest
Massachussets Institute of Technology (MIT), Cambridge, United States
aguest@mit.edu

Mr. Ryan McLinko
Massachussets Institute of Technology (MIT), Cambridge, United States
mclinkor@mit.edu

Mr. Paul D. Wooster
DevelopSpace Initiative, Inc., Redondo Beach, United States
paul@developspace.net

ABSTRACT

Open innovation is an emerging concept for the development of space systems based on a collaborative knowledge management approach that uses sources of knowledge and information both internal and external to the developing organization. A new open source engineering organization, the DevelopSpace Initiative, Inc., has been created to aid in building up the technical foundations for human space activities in an open-source manner. DevelopSpace has created a web-based platform for space system development projects, including offering engineering reference information and engineering models relevant to the development of space systems. The DevelopSpace community is currently engaged in a variety of open engineering projects, including the development of a minimalist architecture for near-term human Mars missions. This minimalist architecture is centered on a one-way mission scenario with crews going to Mars to stay. The initial objective for this approach to human Mars missions is the establishments of a crewed “toehold” which can be the nucleus for expansion into a full-size colony over time. In designing the architecture, the emphasis is on minimum development of new systems and technologies to make near-term execution of the mission feasible. In the context of open innovation and engineering, the minimalist Mars project will support future human Mars mission architecting efforts by exploring a new part of the human Mars mission architecture space which potentially offers significant reductions in overall cost and complexity, defining and prioritizing system and technology development needs for an initial human Mars toehold, as well as by providing innovative system- and subsystem-level design approaches to living on the surface of Mars. This project is intended to highlight near-term developments that can be undertaken in an open source manner to facilitate the eventual undertaking of a mission of this type, and with benefits for human space development more generally.

1. INTRODUCTION

The human exploration of Mars is generally seen as the ultimate goal for human spaceflight in the foreseeable future. Mars offers interesting opportunities for science, both in terms of planetology and the potential for discovering extraterrestrial life [1]. More importantly, however, among the planets of the Solar System Mars is uniquely suited to establishing a permanent human presence away from our home planet Earth: it has a high surface gravity, is relatively close to the Earth (and therefore relatively easy to reach), and has extensive resources of all the basic elements and compounds necessary for sustaining a human community, specifically: carbon, oxygen, nitrogen, and water [1,2]. This is the major difference to the lunar surface (another proposed location for colonization), which is equally hard to reach as the Martian surface from an energy perspective (no atmosphere for braking), but is virtually devoid of carbon and nitrogen, and provides only small amounts of hydrogen.

Serious investigation of the technical feasibility of a human mission to the surface of Mars was begun with Wernher von Braun's fundamental design study "The Mars Project" from 1953 [3]. Further feasibility and design studies were conducted over the following decades [4,5,6,7], culminating in Dr. Zubrin's Mars Direct architecture [8] and the NASA Mars Design Reference Mission architectures [9,10], all featuring the use of in-situ resources for the production of propellants and consumables. The advent of the Vision for Space Exploration in the year 2004 [11] with its long-term goal of human expansion into the Solar System rekindled interest in the technical feasibility of human Mars exploration [12,13].

Previous analyses of human Mars exploration have focused on true "exploration": limited duration round-trip missions which provide temporary access to the Martian surface, typically developed and operated by government agencies. In this paper we explore an alternative approach, both in terms of the mission architecture and the proposed development approach: the focus is on the establishment and sustainment of a permanent human presence in a minimalist fashion using one-way trips to Mars (as a lower-complexity and lower-cost alternative to round-trip missions); the intended development approach also leverages open source engineering and innovation to bring additional resources to bear on the activity and lower the direct financial outlay required to undertake the mission.

It is important to note that the goal of the work presented in this paper is to establish the feasibility one-way human Mars mission and identify areas of work where near-term open-source projects can make significant contributions, rather than developing a detailed reference design that is intended to be implemented as presented.

Section 2 of this paper explores the motivations for and capabilities of open source engineering / platforms; Section 3 provides an overview of the specific open source project which is the basis for the development of the Minimalist Human Mars Mission architecture; Section 4 describes the technical architecture itself; Section 5 lists opportunities for future work both on the system-level and with regard to specific enabling technologies and capabilities identified in the project, and Section 6 provides a summary and major conclusions.

2. OPEN PLATFORMS AND CAPABILITIES

Today the space industry is exploiting knowledge and capabilities mainly created in 1960´s and 70´s to design and develop exploration technologies. For further fast-paced developments new knowledge creation routines have to emerge. Increasing diversity and velocity of learning will push space explorers to execute an Open Innovation strategy. This is also vital to bring down innovation costs, find new external knowledge, and create corporate growth in a more efficient way [14].

Open innovation is an emerging concept for the development of space systems based on a collaborative knowledge management approach that uses sources of knowledge and information both internal and external to the developing organization. Potential benefits of the open innovation approach to space systems development include: reduced development expenditures through re-use of externally generated information or co-development with external partners, and an equivalent reduction of developmental risk. In addition, open innovation can also lead to improvement of the definition of mission requirements and overall mission architectures.

A new organization, DevelopSpace, has been created to aid in building up the technical foundations for human space activities in an open manner. DevelopSpace is a non-profit, tax-exempt organization based in the United States, although open to contributors from around the world. DevelopSpace's aim is to apply open source concepts towards all aspects of space systems development, including not only in the software domain but also hardware and overall system design, as well as associated reference materials. DevelopSpace has created a web-based platform for space system development projects, also offering engineering reference information and engineering models relevant to the development of space systems, hosted at DevelopSpace.net.

DevelopSpace.net is intended to enable a wide variety of individuals and groups to participate in the exploration, development, and utilization of space and thus build a sustained community working towards human expansion into space. The DevelopSpace.net website offers project hosting and other services for those interested in developing space systems in an open manner. Current resources available to projects include:

- Project-based wiki pages to enable the collaborative development of project and design documentation, reference lists, and general catalogs of resources available to those involved in that project or looking to create a similar project. The wiki pages have a similar format to articles in Wikipedia, and any registered user can edit and add to the pages in a straightforward manner to increase the quantity and quality of information associated with a project.
- Subversion repositories to help projects share and collaboratively edit files. Subversion (or SVN) is a version control system which tracks all revisions of the files it manages. While created primarily for assisting software development teams, Subversion is useful whenever a group or individual has a set of files they want to update over time without losing revisions. Subversion enables multiple users to access the same repository and make updates in a safe fashion, unlike a simple file storage system where one person's updates can over-write another's. All models are accessible in the specific project SVN. Write access to the repository requires approval on a per-project basis, although all repositories are publicly readable so that anyone can see the material that has been generated and build upon it as they see fit.
- Project mailing lists, with publicly available archives. These mailing lists can be used to organize project activities and discuss on-going technical activities and updates, whether within SVN, on the wiki-pages, or elsewhere. The publicly accessible archives allow individuals new to a project or interested in getting a sense for the activities of the project to look through previous mailing list postings.

DevelopSpace is also quite willing to expand the project hosting infrastructure available to meet the needs of the DevelopSpace community. In addition to working directly on space-related technical projects, the community is welcome to contribute to the development of the DevelopSpace.net infrastructure.

3. MINIMALIST HUMAN MARS MISSION ARCHITECTURE PROJECT

A portion of the growing DevelopSpace community is currently engaged in the development of a minimalist architecture for near-term human Mars missions. Specifically, the project investigates the feasibility of establishing and sustaining a group of people on the surface of Mars indefinitely. The concept would be to enable initial flights within 1-2 decades with a goal of establishing a human "toehold" on Mars, with a small number of people living on Mars indefinitely. Such a "toehold" would provide essential experience to the long-term prospects of establishing a larger human colony on Mars, and could also serve as the nucleus for the later establishment of such a larger colony.

There were four objectives for the project, partly related to human Mars settlement and partly to the further development of the DevelopSpace open engineering platform:

- To determine what would be involved in implementing a sustained human presence on Mars in the near future
- To compare the cost of a roundtrip Mars mission or of providing the toehold colony with the capability for emergency evacuation back to Earth, as compared to the cost required to maintain the toehold colony indefinitely on the surface of Mars (without return capability)
- To gain an understanding of the financial needs and the potential time phasing for near-term Mars colonization

- To further develop the DevelopSpace.net infrastructure through identification of infrastructure needs

The project began at the end of March 2008; a comprehensive review of the project work is planned in October 2008. The project team involved 9 members who were geographically distributed; locations included California, Massachusetts, Arizona, Colorado (in the US), and Estonia and Germany in Europe.

In order to distribute effectively the information materials between project team members a project website [15], a project SVN repository [16], and a mailing list was created on DevelopSpace.net (see http://wiki.developspace.net/MinMars). The DevelopSpace library, in particular references for subsystem technologies, was also utilized as part of this project.

To aid in coordinating activities and review results, discussions were held over tele-conference approximately every second week starting in April 2008. In addition, individual team members interacted bilaterally as necessary. All results and models are published and available on the project SVN [16] or via the project's wiki pages.

The following section provides an overview of the current integrated technical results of the Minimalist Human Mars Mission project.

4. MINIMALIST HUMAN MARS MISSION TECHNICAL ARCHITECTURE

As mentioned above, the Minimalist Mars approach is focused on establishing a permanently inhabited "toehold" on the surface of Mars as an alternative to round-trip human Mars exploration and as a potential nucleus for the establishment of a larger colony. While an emergency Earth return capability could be considered as a risk-reduction option (see suggestions for future work in Section 5), the nominal scenario is that the toehold crew would go one-way to Mars and live out the rest of their lives on the surface of Mars while being re-supplied as necessary from Earth. This nominal scenario is the focus of the analysis presented in the sections below.

System- and subsystem-level technical and operational analyses were carried out to assess feasibility and requirements of such an initial Mars surface toehold; specific results from these analyses in the areas of Earth-Mars transportation, surface infrastructure and operations, surface power generation and energy storage, as well as re-supply and In-Situ Resource Utilization (ISRU) are presented in the subsections below. The discussion is concluded by the outline of a notional flight manifest for delivering infrastructure and crew to the surface of Mars and subsequently sustaining the crew indefinitely.

4.1. Earth-Mars Transportation Approach

The Earth-Mars transportation concept is based on chemical propulsion for Earth departure and injection towards Mars (LH_2/LOX propulsion), aerocapture at Mars, subsequent aerodynamic entry, and propulsive final descent and landing (LCH_4/LOX propulsion). Earth departure from Low Earth Orbit (LEO) is achieved by sequentially burning two Earth departure stages which are attached to the trans-Mars payload (see Figure 1). This approach is conceptually very similar to other approaches proposed in the literature [13] in terms of operations and technologies used (not necessarily in terms of scale).

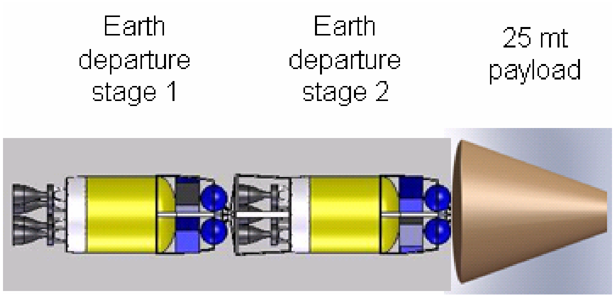

Figure 1: Earth departure stack with two 25 mt LOX / LH_2 propulsion stages per 25 mt payload

The launch strategy was based on commercial launch vehicles in the heavy EELV class, i.e. approximately 25 mt payload capability to a 28.5 degree inclination LEO. Specifically, the SpaceX Falcon 9 heavy was chosen as a reference vehicle [17], although other vehicles such as the Delta IV Heavy, Ariane V, Proton, or Atlas V Heavy could also be used with little to no modification to the high-level architecture, albeit at some reduction in payload capacity and an increase in launch cost compared to the proposed SpaceX Falcon 9 heavy. Using two 29 mt LH_2/LOX Earth departure propulsion stages, each launched on a Falcon 9 heavy, a 25 mt payload can be injected towards Mars (the payload itself is also launched on a Falcon 9 heavy). It should be noted that it may be possible to use LOX / kerosene propulsion stages as an alternative to LH_2/LOX propulsion stages for Earth departure; this could enable re-using the design of the upper stage of the Falcon 9 heavy for the Earth departure stage.

For Mars aerocapture and EDL of the 25 mt payload, a blunt-body entry vehicle was chosen. Figure 2 provides a comparison of entry vehicle properties to the Mars Science Laboratory MSL entry vehicle [22]. The most pronounced difference to MSL is the significant increase in ballistic coefficient and vehicle / payload mass, leading to higher Mach-numbers at the same altitude above Mars mean and potentially prohibiting the use of supersonic parachutes because the vehicle never slows down sufficiently and is too massive to use current Mars parachute technology.

Vehicle	MinMars	MSL
Ballistic coefficient [kg/m2]	433	115
Aeroshell diameter [m]	7	4.6
Entry velocity [km/s]	4.5 (orbit)	6 (direct)
Landing altitude	<-2 km	< 2 km
Active entry guidance	Yes	Yes

Figure 2: Comparison of planned entry body to Mars Science Laboratory entry vehicle [22]

The effect of increasing the ballistic coefficient can be mitigated somewhat by choosing a lower landing altitude than achievable with MSL; for the analysis presented here a final landing altitude of – 2 km or less was assumed, allowing for additional braking in denser parts of the atmosphere. The vehicle is slowed down to Mach 3 several km above the surface, at which point propulsive separation of the forebody and back shell are carried out and the main LCH_4/LOX propulsion system is started for final descent and landing (so parachutes are not required for deceleration at all).

In order to estimate the payload mass achievable with this entry vehicle, the aeroshell mass was scaled up linearly from the Mars Phoenix lander aeroshell [21] with protected mass (propulsion stage and surface payload), and the propulsion stage dry mass was calculated based on a structural factor derived from descent stage designs used as part of the NASA Mars Design Reference Mission 3.0 [9]. Based on these assumptions, 10 mt of useful surface payload based on a 25 mt entry body appear to be achievable, although significant technology development with regard to forebody heat shield material and design as well as with aeroshell separation mechanisms may be required.

4.2. Surface Infrastructure and Operations

Initial Mars toehold infrastructure includes all elements which are placed on the surface prior to arrival of the crew or together with the crew. Additional infrastructure may be deployed after the crew arrives on Mars to decrease operational risk and / or decrease re-supply needs.

The initial crew of 4 is sent to Mars in two groups of two crew members. Each group arrives in a habitat mounted inside the aeroshell on top of the propulsion stage for final descent and landing on Mars. The habitat has two levels; during the Earth-Mars transit the lower level is intended as living space and storage area for supplies, the upper as sleeping and private area for the crew. Upon arrival on the surface of Mars, the crew attaches a pre-deployed inflatable module to each habitat, significantly enhancing the pressurized volume and floor area available per crew member. In the event of a failure of one of the habitats, the other is capable of supporting the entire crew until repairs can be made.

In addition to attaching inflatable modules, activities of the crew following landing are:

- Deployment of surface power generation and storage systems
- Deployment of telemetry and communications equipment for contact with Earth
- Deployment and operation of ISRU units for oxygen and water generation

The crew is supported in these activities by two un-pressurized rovers, one delivered with each habitat. Each unpressurized rover is capable of carrying the entire crew in the event of an emergency, eliminating drive-back constraints and thus providing the crew with access to targets 20 km or more from base [18].

After the initial build-up phase, regular operations for the crew include re-supply of their habitats with pressurized and unpressurized consumables, maintenance of surface infrastructure, exploration traverses in the vicinity of the base, as well as installing new equipment and infrastructure delivered from Earth.

4.3. Surface Power Generation and Storage

A system-level analysis of Mars surface power generation and storage concepts for the toehold was carried out, including options such as nuclear power, tracking solar arrays + batteries or regenerative fuel cells, non-tracking solar arrays + batteries or regenerative fuel cells, as well as dynamic radioisotope power generation units. A detailed description and the full results from this analysis are published in a separate paper at IAC 2008 [23].

Figure 3 shows results for an analysis of these power system concepts for an equatorial location in the form of average power per total system mass as a function of the average power level:

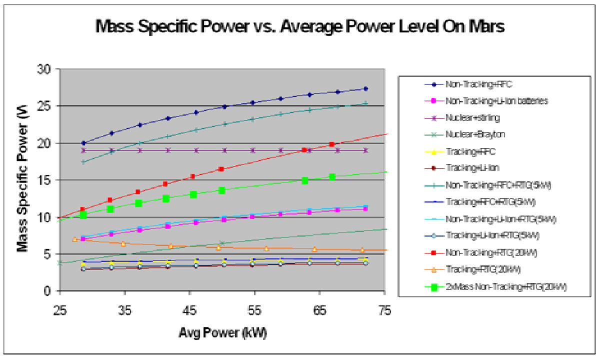

Figure 3: Results from equal-energy analysis of surface power system concepts for Mars equatorial location

The above analysis was based on equal-energy per day: each system provides the same amount of energy to the user every day, albeit with different power profiles. The nuclear options provide steady power output, whereas the solar options provide the majority of the energy during the day (i.e. when the sun is shining), and only provide a steady 20 kW at night for basic habitat and communications functionality.

The results in Figure 3 suggest that on an equal-energy basis non-tracking solar arrays are mass-competitive with nuclear power systems; a non-tracking solar power system with lithium-ion batteries (~11 W/kg) was therefore selected as the baseline power generation and energy storage system for the Mars toehold in order to side-step the significant development cost and risk as well as the political sustainability risks associated with nuclear systems.

The effectiveness of Mars surface solar power is, of course, strongly dependent on toehold latitude (variations in solar incidence angle as well as day-length). A high-level analysis of this dependence was carried out; Figure 4 shows quantitative results. Nuclear power solutions are unaffected by changes in latitude; for solar power solutions, northern latitudes are preferable to southern latitudes. The higher performance for northern latitudes comes about as a result of the eccentricity of Mars' orbit about the Sun and the fact that the northern hemisphere winter corresponds with Mars being closer to the Sun, diminishing the effect of the shorter illuminated duration during the winter. High performance can be achieved for latitudes between 20 and 40 degrees north, with a maximum at about 30 degrees north. The baseline latitude for the toehold was assumed to be close to the maximum performance point.

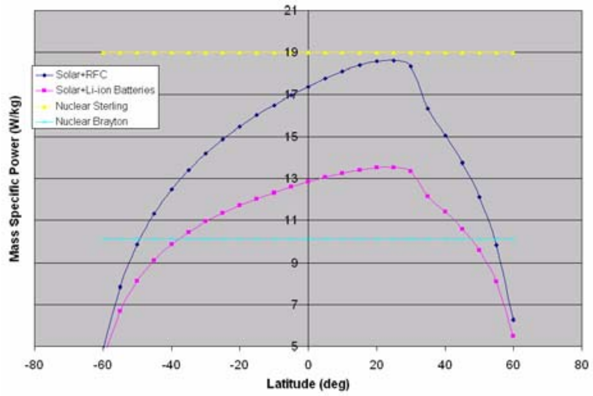

Figure 4: Results from equal-energy analysis of surface power system concepts as a function of Mars latitude

4.4. Toehold Re-supply and Logistics

Re-supply of the Mars surface toehold is the long-term driver for transportation needs to the Martian surface, as well as the limiting factor for expansion of the crew size inhabiting the toehold (for a given set of transportation resources).

The re-supply requirements of the toehold are mostly determined by the consumables and spare parts needs of the life support and crew accommodations systems of the toehold. Table 1 provides an overview of the design choices for important Mars toehold life support and crew systems; quantitative information can be found on the SVN under {models/logistics} [16]:

Table 1: Overview of life support and crew accommodations subsystem designs

Function	Technology choice
CO2 removal	4-bed molecular sieve system
O2 provision	Zirconia electrolysis (ISRU)
Food provision	Stored, mostly dehydrated food
Hygiene provision	Expendable, mostly dry items
Clothing	Washing machine + dryer
Humidity removal	Condensing heat exchanger
Water management	Multifiltration + distillation
Water acquisition	Extraction from Martian soil

Water regeneration by filtration and distillation is used both for re-cycling water inside the habitats and for cleaning water acquired in-situ from the Martian soil through. At present the water reclamation systems is based on the design used for the International Space Station (ISS) and therefore has relatively high re-supply requirements. Carbon dioxide and humidity removal are regenerative, and no in-situ food production is planned initially.

Using the above technology portfolio, a re-supply requirement of 1700 kg / person / opportunity can be achieved; this includes spare parts as well as tare mass to account for the logistics vessels required to deliver supplies and spare parts.

Figure 5 provides a relative breakdown of the mass contributions of the different life support and crew accommodations functions to the overall remaining re-supply requirement. It is apparent that food is the major re-supply item, followed by spare parts for the water reclamation system. Detailed analyses of options for closure of the food loop have not been carried out; however, initial analyses suggest that large surface infrastructure masses are required to achieve significant reductions of the food re-supply need. This indicates that meaningful closure of the food loop may only be achieved once the capability for in-situ manufacture of the required infrastructure has been built up.

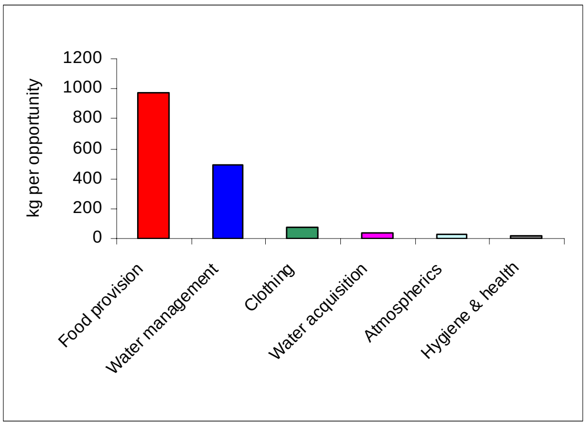

Figure 5: Breakdown of re-supply needs by function, including spare parts and tare masses for logistics vessels

The water reclamation re-supply is primarily driven by spare parts for the filtration units; the use of alternatives to filtration is being explored and may yield further reductions of the re-supply needs in this area.

4.5. In-Situ Resource Utilization (ISRU)

In general, the purpose of In-Situ Resource Utilization (ISRU), or "living off the land", is to harness and utilize space resources to create products and services which enable and significantly reduce the mass, cost, and risk of near-term and long-term space exploration. Mars has a vast resource base available for human use, including the carbon dioxide, nitrogen, argon, and traces of water vapor in the atmosphere and water ice in near-surface regolith, which are of the most practical use for a toehold outpost. Suitable processing can transform these raw resources into useful materials and products [19]. Incorporation of ISRU capabilities can provide multiple benefits for individual missions and/or architectures as a whole: mass, cost & risk reduction; mission enhancements and flexibility; enabled capabilities.

The baseline ISRU concept for the Mars toehold is shown in Figure 6; the solid lines represent initial ISRU capabilities whereas the broken lines represent possible expansion paths:

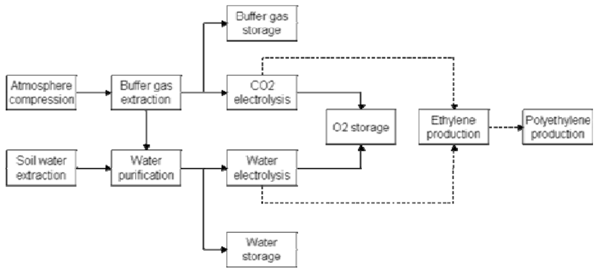

Figure 6: Baseline ISRU architecture for the initial Mars toehold, featuring oxygen and water acquisition by ISRU

The initial ISRU capability is focused primarily on providing breathing oxygen and make-up water for the crew, and in addition buffer gases for habitat re-pressurization. Oxygen is generated from atmospheric CO_2 using the zirconia electrolysis process; water is extracted from the soil using green-house tent systems with condensers proposed by Zubrin, et al. [2,8].

Possible expansion paths include using carbon monoxide exhaust from the zirconia electrolysis process in conjunction with hydrogen to synthesize ethylene, which in turn can be used as feedstock for polyethylene production. Producing polyethylene provides the bases for an indigenous plastics production capability which has the potential to significantly reduce spare part re-supply needs as well as to provide materials for building up a food production infrastructure.

The reverse water-gas shift process (RWGS) was analyzed as an alternative to using the zirconia electrolysis process; RWGS would provide the same capabilities as zirconia electrolysis, albeit at potentially reduced mass and power needs. Figure 7 provides an overview of a RWGS-based ISRU architecture for the Mars toehold; the major difference is that RWGS substitutes zirconia electrolysis, but as it does not directly produce oxygen it interfaces directly with water electrolysis. RWGS produces carbon monoxide which may be fed into an ethylene production unit (as for the baseline architecture).

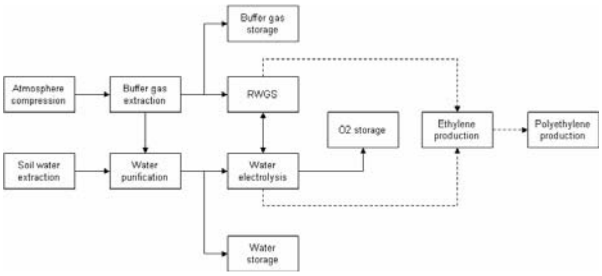

Figure 7: Alternative ISRU architecture for the initial Mars toehold with RWGS instead of zirconia electrolysis

The ISRU analyses are available on the project SVN under {models/ISRU} [16]. While only two architectures are highlighted here, a variety of options exist which could be pursued in preparation for a human toehold mission. Our logistics analysis indicates that the initial emphasis should be on the provision of water, oxygen, and buffer gas (nitrogen and/or argon) for the toehold colony.

4.6. Earth-Mars Transportation Manifest

In this section we describe the overall operational approach to transporting infrastructure, crew, and supplies to the surface of Mars. It is assumed that each opportunity two 25 mt payload packages ("flights") are sent to the surface of Mars, yielding a total of 20 mt of net surface payload per opportunity. This transportation capability would require a total of six Falcon 9 heavy launches every opportunity (26 months), or approximately 3 each year. The following is an overview of the current manifest for Mars surface payload:

- **Opportunity 1 (no crew):**
  - Flight 1: surface power, inflatable habitat, pressurized supplies, communications tower, ISRU systems (for water extraction)
  - Flight 2: surface power, inflatable habitat, pressurized supplies, communications tower, ISRU systems (for water extraction)
- **Opportunity 2 (no crew):**
  - Flight 1: pressurized supplies
  - Flight 2: pressurized supplies
- **Opportunity 3 (1st crew of 4):**
  - Flight 1: habitat with 2 crew, supplies, unpressurized rover
  - Flight 2: habitat with 2 crew, supplies, unpressurized rover

Uncrewed flights during the first two opportunities are used to pre-position essential equipment such as pressurized supplies (initial consumables for crew after Mars arrival safety stock) and essential surface infrastructure (such as communications, ISRU, habitation). During the first two opportunities a cache of supplies sufficient for two opportunities is built up.

In the third opportunity 4 crew members are sent to Mars, 2 on each flight. After the third opportunity (and the arrival of the crew), it is assumed that the immediately following opportunities will have 2 uncrewed flights each: one flight delivering consumables for sustaining the crew's existence on Mars, the other flight delivering additional infrastructure for closing re-supply loops (in particular the food and spare part loops). Once loops have been closed sufficiently to allow for sustaining 6 crew with a single cargo flight, one of the two flights in an opportunity can be utilized to send another 2 crew members to the surface of Mars; however, the focus to date of the analysis has been on successfully establishing 4 crew on the surface of Mars and sustaining them there indefinitely, rather than in growing the colony size.

The launch and transportation manifest is available on the Minimalist Human Mars Mission project SVN under {models/transportation} [16].

5. OPPORTUNITIES FOR FUTURE WORK

The open engineering / open innovation project described in this paper investigated the technical and operational feasibility of an initial Mars toehold and carried out system- and subsystem-level designs of the major transportation and infrastructure elements. The focus of the project was on establishing the feasibility of deploying and sustaining a crewed Mars toehold and with possible slow expansion of the toehold capabilities.

One avenue for future work is the system-level analysis of ways to significantly increase the capabilities of the Mars surface infrastructure to support a significantly larger population size, i.e. an investigation for the major developments required to enable colonization. Based on the analysis carried out so far, closure of the food and spare parts loops as well as in-situ manufacturing of materials for construction appear to be enabling for a significant increase in crew size. An increase in the flight rate beyond 2 flights per opportunity may also be required, and in any case would be beneficial for more rapid growth of the outpost.

A second avenue for future work is the analysis of the added cost and the potential risk benefits of an emergency Earth return capability. Such a system would likely be based on a direct return operational approach with Earth return propellant being produced locally on the surface of Mars[5]. An emergency Earth return capability could lead to the reduction of safety stocks and of redundancy required in the surface infrastructure, albeit at increased development cost and reduced robustness of the human presence on Mars.

These first two opportunities for future work will be explored as part of the continuation of the Minimalist Human Mars Mission project, along with continuing architecture definition activities for the initial toehold itself; results will be accessible on the existing project website and SVN [15,16].

A third avenue for future work is more detailed analysis and development of technologies and systems that have been identified as being desirable for future human Mars exploration, in particular in the context of the one-way toehold approach. Efforts in these areas can significantly reduce the uncertainty and cost associated with the implementation of the toehold outpost concept, thus increasing the likelihood the mission would be undertaken. The following is an abridged list of selected high-interest or enabling technologies / capabilities which were identified during the Minimalist Human Mars Mission project, with an emphasis on areas which could be developed by relatively small groups working in an open source engineering manner:

Transportation technologies / capabilities:

- Automated Mars landing and hazard avoidance navigation systems
- Mars in-situ propellant production friendly rocket combustion / performance characterization (i.e., ethylene/oxygen; methane/oxygen); more important for Earth return capability
- Large-scale (20mt+) Mars aero-entry (and EDL more generally) technology

Surface power technologies / capabilities:

- Automated, large scale (football field+) solar array transport, surface deployment, and maintenance systems
- High energy density electrical power storages systems (aiming in particular towards high energy density relative to Earth imported mass)

Logistics and ISRU technologies / capabilities:

- Mars atmosphere collection systems
- Mars permafrost mining systems
- High capacity Mars surface cryo-coolers (options for soft/medium cryogens (e.g., liquid oxygen, methane, ethylene), or also for hard cryogens (i.e., liquid hydrogen))
- ISRU chemical processing systems (e.g., water electrolysis, Sabatier, Reverse Water-Gas Shift, carbon dioxide electrolysis, ethylene production, etc.)
- High closure physical-chemical life support systems (e.g., air revitalization, water recycling)

Surface exploration technologies / capabilities:

- Mars surface communication and navigation systems (e.g., for rovers)
- Long-term use Mars surface EVA suits
- Very long distance surface mobility systems (including with people)
- Solar flare / SPE warning systems

The full list can be found on the Minimalist Human Mars Mission project website [15]. The intent is that for a number of high-interest technologies in this list, separate open engineering projects would be initiated to either establish feasibility or carry out more detailed analysis and design activities intended to increase technology readiness. This way, the open engineering community can contribute to bringing human Mars exploration closer to reality. For Mars solar surface power such a spin-off project has already been created with the objective to establish system-level feasibility of non-tracking Mars surface power concepts with batteries or regenerative fuel cell energy storage [20].

Our project team would like to encourage any and all who wish to explore areas within this list, or which would contribute more generally to the establishment of a human toehold on Mars, to do so. The infrastructure put in place by DevelopSpace is open to all who wish to contribute towards its goals, and DevelopSpace is quite happy to host additional projects along these lines.

6. SUMMARY AND CONCLUSION

This paper presents the results from an open engineering / open innovation effort in the area of human Mars mission design. A multi-disciplinary team with members located in different parts of the US and Europe engaged in a feasibility study of establishing and sustaining a crewed toehold on the surface of Mars. The team used open engineering tools provided by the DevelopSpace platform, such as a wiki-based webpage, an SVN repository, a project mailing list, and an online technical reference library; in addition regular tele-conferences were carried out with the entire team, as well as bilateral interaction between team members.

Technical results from the project indicate that establishing and sustaining a Mars surface outpost with an initial crew of four is achievable using heavy EELV-class launch vehicles with a frequency of 6 launches per opportunity. Significant pre-positioning of surface infrastructure is required (spread over 2 mission opportunities); after the deployment of the 4 crew members the outpost can be sustained by 3-6 launches per opportunity (depending on the desired level of expansion of capability on the surface of Mars).

A number of high-interest and enabling technologies and capabilities have been identified, such as Mars aerocapture and EDL of 25 mt class payloads, Mars solar surface power generation, and toehold-class in-situ consumables production (i.e., water and atmospheric gas generation); these will be explored further in dedicated open engineering projects.

ACKNOWLEDGEMENTS

We would like to thank all of those involved in DevelopSpace who have made (and are continuing to make) open source engineering contributions relevant to human expansion into space. We would like to specifically acknowledge the efforts of members of the project team involved in developing the Minimalist Human Mars Mission architecture: Chase Cooper, Emily Grosse, Aaron Schultz, and Andrew Tubbiolo.

REFERENCES

[1] Hoffman, S., Kaplan, D. (editors), The Reference Mission of the NASA Mars Exploration Study Team, NASA SP-6017, Johnson Space Center, Houston, Texas, 1997.

[2] Zubrin, R., et al., The Case for Mars, Free Press, Touchstone Edition, 1997.

[3] von Braun, W., The Mars Project, University of Illinois Press, Urbana and Chicago, 1991.

[4] Goodwin R, Mars: The NASA Mission Reports - Volume 1, Apogee Books Space Series # 10, June 2000.

[5] Ride SK, Leadership and America's Future in Space, Report to the NASA Administrator, August 1987.

[6] Office of Exploration, Exploration Studies Technical Report, NASA TM 4075, December 1988.

[7] Cohen A., Report of the 90-Day Study on Human Exploration of the Moon Mars, NASA Johnson Space Center, November 1989.

[8] Zubrin, R., et al., Mars Direct: A Simple, Robust, and Cost Effective Architecture for the Space Exploration Initiative, AIAA-1991-329-394.

[9] Drake, B. G. (editor), Reference Mission Version 3: Addendum to the Human Exploration of Mars, NASA SP-6017-ADD, Johnson Space Center, Houston, Texas, 1998.

[10] Drake BG, Exploration Blueprint - Data Book, NASA JSC-63724, Released February 2007.

[11] The President of the United States of America, Vision for Space Exploration, The White House, January 2004.

[12] Draper/MIT CE&R Study: Final Report, Cambridge, MA, September 2005.

[13] Wooster PD, Hofstetter WK, Crawley EF (2005) The Mars-back Approach to Moon-Mars Exploration System Commonality, 1st Georgia Tech Space Systems Engineering Conference, November 8-10, 2005.

[14] Aeronautics Innovation: NASA's Challenges and Opportunities (2006) Stephen A. Merrill, Editor, Committee on Innovation Models for Aeronautics Technologies, National for a Changing World Design Project Report Summer Session Program 1997.

[15] Minimalist Mars Mission project website: http://wiki.developspace.net/Minimalist_Human_Mars_Mission, September 2008.

[16] Minimalist Mars Mission SVN website: http://svn.developspace.net/svn/minmars/, September 2008.

[17] Space Exploration Technologies – Falcon 9 Heavy Website: http://www.spacex.com/falcon9_heavy.php, accessed September 1, 2008.

[18] Hofstetter WK, Wooster PD, Crawley EF (2006) Extending NASA's Exploration Systems Architecture towards Long-term Crewed Moon and Mars Operations, AIAA Space Operations Conference 2006, Rome, June 19-23, 2006.

[19] NASA In-Situ Resource Utilization (ISRU) Capability Roadmap Final Report May 19, 2005

[20] Mars Surface Solar Power project website: http://wiki.developspace.net/Mars_Solar_Power, September 2008.

[21] Phoenix Mars landing press kit, JPL / NASA 2008.

[22] Braun RD, Manning RM, Mars Exploration Entry, Descent and Landing Challenges, IEEE, 2006.

[23] Cooper C, Hofstetter WK, Hoffman JA, Crawley EF, Assessment of Architectural Options for Surface Power Generation and Energy Storage on Human Mars Missions, IAC-08-A3.3.B, International Astronautical Congress, Glasgow, September / October 2008.