Technology Needs to Support Future Mars Exploration

Erik N. Nilsen[1], John Baker[2]
Jet Propulsion Laboratory, Pasadena, CA 91109
Randolph P. Lillard[3]
NASA Headquarters, Washington DC, 20546

The Mars Program Planning Group (MPPG) under the direction of Dr. Orlando Figueroa, was chartered to develop options for a program-level architecture for robotic exploration of Mars consistent with the objective to send humans to Mars in the 2030's. Scientific pathways were defined for future exploration, and multiple architectural options were developed that meet current science goals and support the future human exploration objectives. Integral to the process was the identification of critical technologies which enable the future scientific and human exploration goals. This paper describes the process for technology capabilities identification and examines the critical capability needs identified in the MPPG process. Several critical enabling technologies that have been identified to support the robotic exploration goals and with potential feedforward application to human exploration goals. Potential roadmaps for the development and validation of these technologies are discussed, including options for subscale technology demonstrations of future human exploration technologies on robotic missions.

I. Introduction

In March 2012, NASA established the Mars Program Planning Group (MPPG) under the leadership of Dr. Orlando Figueroa[1]. The charter of the MPPG was to re-plan the U.S. Mars Program in light of the FY 2013 Presidential budget submission and the desire to support humans in Mars orbit in the 2030s. At the conclusion of the deliberations, the MPPG presented a program level architecture for robotic exploration that feeds forward to the future human exploration of Mars, consistent with the desire to return high priority science, and providing opportunities to demonstrate key technologies essential to the future human exploration.

This paper presents an overview of the key technologies the MPPG identified for future robotic and human exploration of Mars. The MPPG looked at the robotic technologies that were necessary for supporting SMD science objectives which also had potential cross-cutting application to future HEOMD needs. In addition, the MPPG examined HEOMD specific technology needs, and identified candidate technologies that could be demonstrated on robotic missions. Lastly, the MPPG presented a notional development/demonstration approach that provided for full scale and sub-scale technology demonstrations in Earth-based and Mars-based environments.

II. Crosscutting Technologies for Science and Human Exploration

The MPPG investigated the technology needs to support the proposed robotic exploration of Mars, with the emphasis on cross-cutting technologies that support both the near term robotic and future HEOMD capabilities. These technologies provide essential capabilities to support high rate communications, greater precision in the delivery of spacecraft to orbit and to the surface of Mars, and delivering larger and more capable payloads for exploration and infrastructure development. The following is a discussion of the specific technologies identified in by the MPPG as providing essential capabilities to support the proposed program architecture.

---

[1] Manager, MSR Advanced Studies, Jet Propulsion Laboratory, M/S 321-630, 4800 Oak Grove Drive, Pasadena, CA 91109, USA, non-member
[2] Manager, Human-Robotic Systems Engineering Office, M/S 321-640, 4800 Oak Grove Drive, Pasadena, CA 91109, USA, non-member
[3] Program Executive for Technology Demonstration Missions, Space Technology Mission Directorate, NASA Headquarters, 300 E Street, SW, Washington DC 20546, non-member

III. Science-driven technology interests with Potential HEO benefit

The MPPG process performed a broad survey of capability needs required to support future robotic and human exploration objectives. The following technologies provide a broad array of capabilities to the robotic exploration endeavor, and also have potential HEO benefit for future human exploration.

A. Autonomous Rendezvous and Docking

The current architecture for MSR presented in the Planetary Science Decadal Survey[2] has the cache of Mars surface material injected into Mars orbit, where it is collected by an orbiting spacecraft for eventual return. Essential to accomplishing that objective is the ability to locate and track the Orbiting Sample (OS), rendezvous with it and capture it. Due to the distance from Earth to Mars, for a robotic mission to accomplish the delicate terminal phase of the rendezvous and the capture operations, autonomous capabilities are required. The ability to acquire the target and maneuver the spacecraft to a rendezvous point, and then successfully capture an inert OS requires the development of advanced space-qualified sensors, capture mechanisms and autonomous rendezvous algorithms and software. Some technologies, such as flash LIDAR, have been demonstrated in limited fashion in Earth orbit.[3] Development of the capability for Mars rendezvous and capture will require advancement of both the sensors and systems.

B. Solar Electric Propulsion

Solar Electric Propulsion (SEP) promises to provide the capability to deliver more mass to Mars more efficiently, and provide the capability to tailor rendezvous conditions. SEP has been proven for deep-space applications on the DS-1 and DAWN missions using gridded ion thrusters. Both of these missions employed thrusters developed under the NSTAR program with a specific impulse of 3100 seconds and producing a thrust of 90 mN each. DAWN employed 10 kW (1 AU) solar arrays to power the three NSTAR thrusters, and will expend ~400 kg of Xenon fuel during its mission.

For Mars robotic exploration, higher performance Hall effect thrusters are being investigated. These thrusters promise significant advantages, including higher power, higher thrust and longer lifetime[4,5]. Figure 1 shows the HIVHAC thruster which is under development at Glenn Research Center, Figure 2 shows the commercial BPT-4000 Hall thruster under test and figure 3 shows the H6MS Hall thruster under test at JPL.

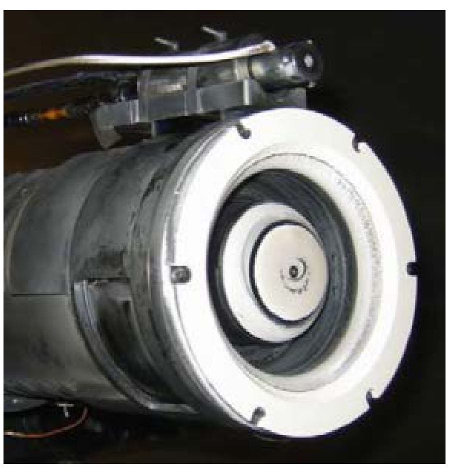


Figure 1. NASA HIVHAC Thruster in testbed

Figure 2. BPT-4000 Hall Thruster under test

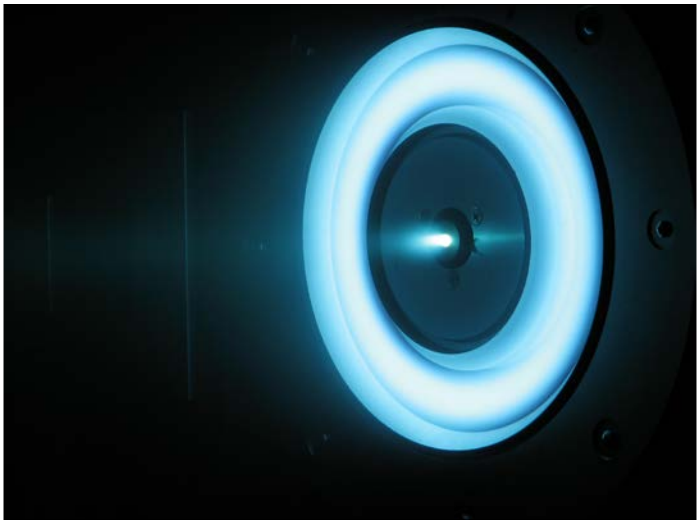


Figure 3. Hall thruster under test (9 kW, 3000 sec Isp)

C. Sample Acquisition, Handling and Caching

For the Mars Sample Return mission, the ability to access, analyze, collect and cache material is essential. The return of surface material for analysis in Earth-based laboratories may provide fundamental scientific insight into the formation and evolution of Mars, as well as providing essential data on habitability directly affect the planning for future human exploration. For MSR, the ability to collect core samples from rock of varying types, collection of loose regolith, and the acquisition of atmospheric samples are all extremely important to meeting potential science goals.

The Curiosity rover has the most sophisticated sample handling system in use on Mars. It includes the ability to drill into rock, collect surface specimens and process material for in-situ analysis. Future missions will require the ability to collect monolithic cores of material, encapsulate and hermetically seal them, and package them for eventual return[6,7]. Figure 4 presents a current proptype of a coring drill.

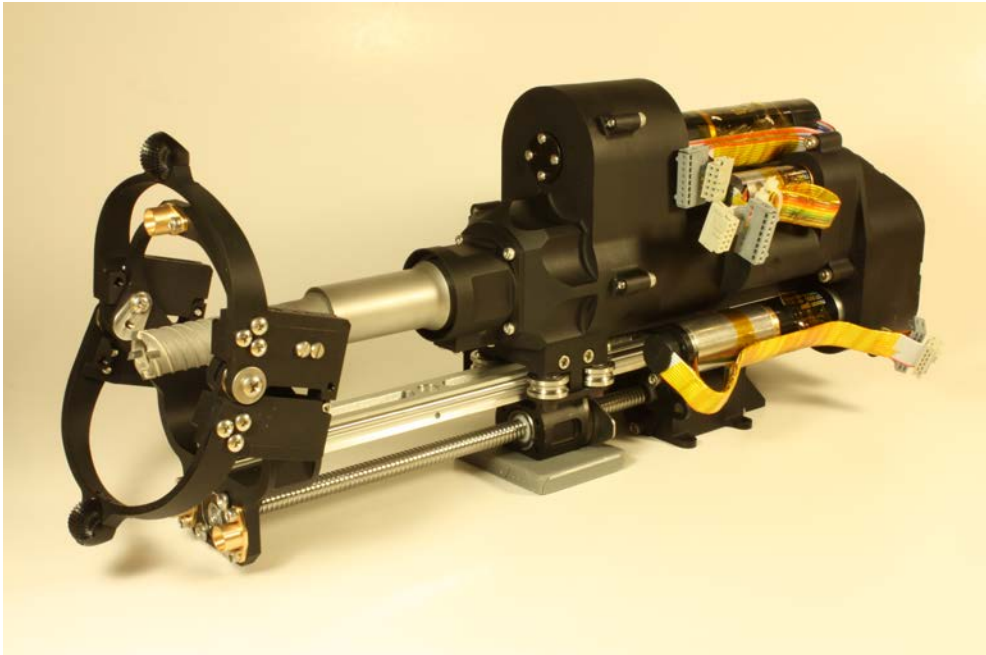


Figure 4. Prototype Rotary Percussive Drill for Mars Exploration (courtesy: Honeybee Robotics)

Future mission capability needs in this area may include deep drilling[8] and specialized handling and processing of material for science or for In-Situ Resource Utilization (ISRU).

D. Deep Space Atomic Clock

The Deep Space Atomic Clock (DSAC) provides an ultra-stable frequency reference that is suitable for deep space navigation and radio science applications. In current practice, deep space missions typically employ an Ultra-Stable Oscillator (USO) to achieve a stable frequency reference on the order of 10^{-13}; however, this isn't sufficient for routine use in radiometric tracking because over time the frequency and time still drift well outside suitable ranges (current two-way Doppler precision is ~ 0.1 mm/sec @ 60 seconds and two-range precision at 1 m) [9]. DSAC promises to increase that stability to 10^{-15} (equivalent to the ground atomic clocks), which makes it viable for routine use with 1-Way data types, and provides multiple benefits. Furthermore, DSAC provides over an order of magnitude performance improvement (on all time scales) relative to atomic clocks that currently fly in Earth orbit.

The primary benefit for Mars exploration is achieving the requisite navigational accuracy using one-way Doppler measurements only. Currently, two-way Doppler measurements using an uplink from the Earth to the spacecraft and then back to the Earth, is used to achieve the high degree of navigational accuracy needed for Mars exploration. By employing atomic clocks to stabilize the frequency reference, the necessary accuracy can be achieved using one-way Doppler measurements (consisting of a downlink signal from the spacecraft to the Earth). This significantly reduces the dedicated Deep Space Network (DSN) antenna demands, and will allow one antenna to provide simultaneous navigation services for multiple platforms at Mars. In addition, the higher precision frequency reference will increase the accuracy of several different radio science measurements.

The key technology challenge for the deep space atomic clock is developing components that are small enough for use in a spacecraft (ground atomic clocks are refrigerator sized) and still perform and survive in the deep-space mission environment. Key factors include surviving vibration and shock loads from the launch vehicle, and shielding DSAC's critical physics components from changing magnetic fields.

E. Optical Communications

Optical communication has been studied extensively for a range of deep space exploration needs, including Mars. A recent analysis indicated that communications requirements will grow by a factor of 10 in the next fifteen years[10] and optical communications is a key to providing that bandwidth. Studies indicate that communication rates of 5-40 MB/sec can be achieved using a reasonably sized system (5W laser with a 30cm telescope for the flight system and a 10M diameter ground receiving antenna)[11].

In operation, the optical communications link would be between a Mars orbiter and the Earth, with high speed communications between surface assets and the orbiter provided by radio frequency links (UHF). The optical communications terminal would be the high speed trunk line between Mars and the Earth, relaying science and engineering data from multiple Mars surface and orbital assets. In future concepts, multiple relay assets in Mars orbit could provide nearly continuous high rate communications for supporting future science and human missions[12].

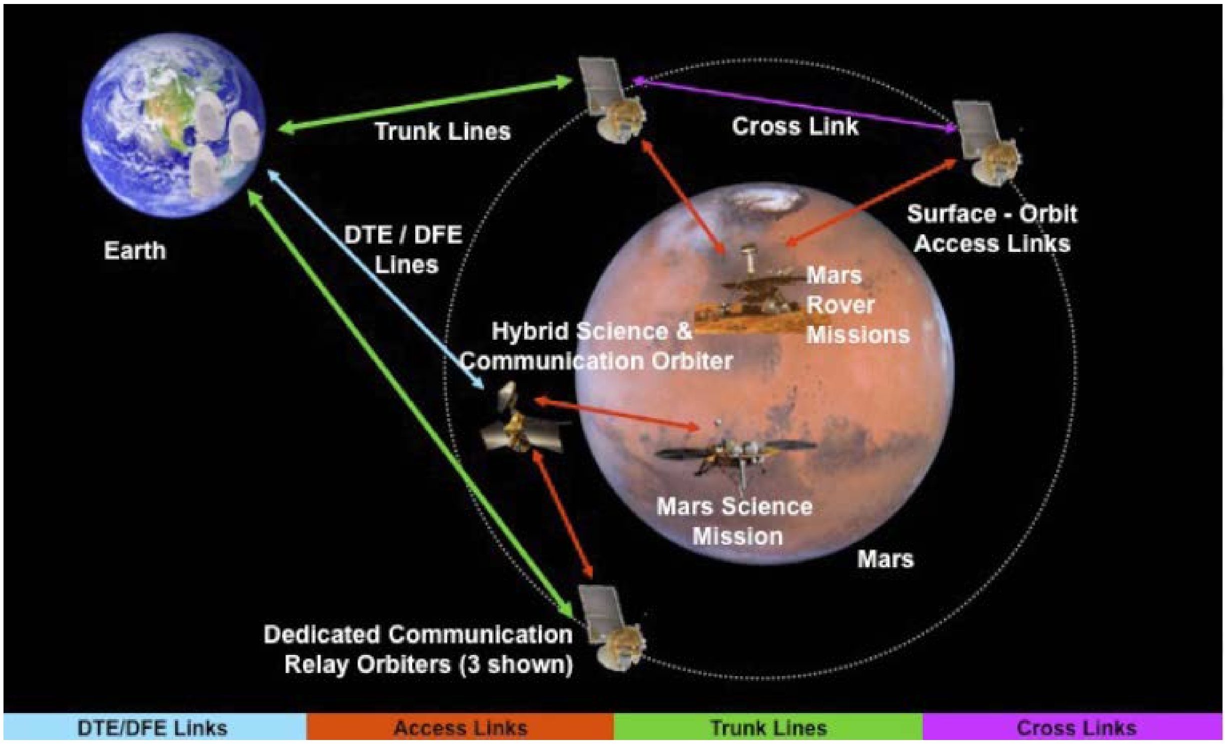


Figure 5. Potential future Mars communications network using high data rate trunk lines

The key technology challenges for optical communication is the development and deployment of a network of ground receiver stations, and the development of 22cm – 30cm optical transceivers for flight systems. For the ground receivers, current concepts are aiming at 1 meter demonstration receivers, with future development of highly sensitive detectors, and low cost 12 meter telescopes.

F. Storable Propellant MAV

The storable propellant Mars Ascent Vehicle (MAV) is a key element of a potential Mars Sample Return (MSR) campaign[13]. In order to place a collected sample of Mars surface material in orbit around Mars, a suitably scaled launch vehicle needs to be delivered to the surface. This MAV concept is specific to MSR, utilizing a storable propellant (either solid or liquid) to deliver small payloads from Mars surface to Mars orbit. Future concepts requiring the delivery of large payloads from Mars surface to Mars orbit (including humans) may require In-Situ Resource Utilization (ISRU) derived propellants and much larger MAVs than the robotic sample return missions.

The storable propellant MAV provides the capability to deliver small payloads (<10 kg) from the surface to a long term stable orbit of Mars. Current concepts deliver this capability using two stage solid-solid rocket motors, however multiple concepts based on two stage liquid propellant motors, or combinations of liquid and solid motors have been studied. The NASA In-Space Propulsion Technology (ISPT) Program has invested in multiple MAV architecture concept studies and Figures 6 and 7 show solid-solid and solid-liquid concepts (LM-ATK partnership), and liquid-liquid (Northrup Grumman Aerospace Systems) concepts.

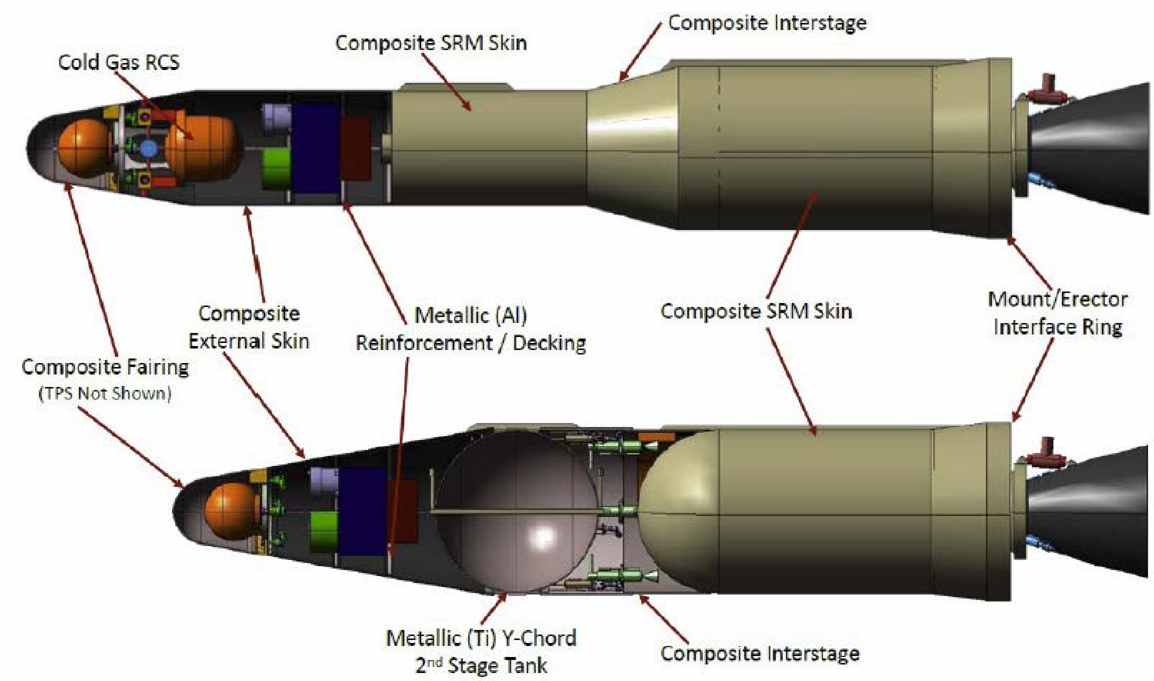


Figure 6. Storable Propellant MAV concepts -solid-solid top, solid liquid bottom (LM-ATK concepts)

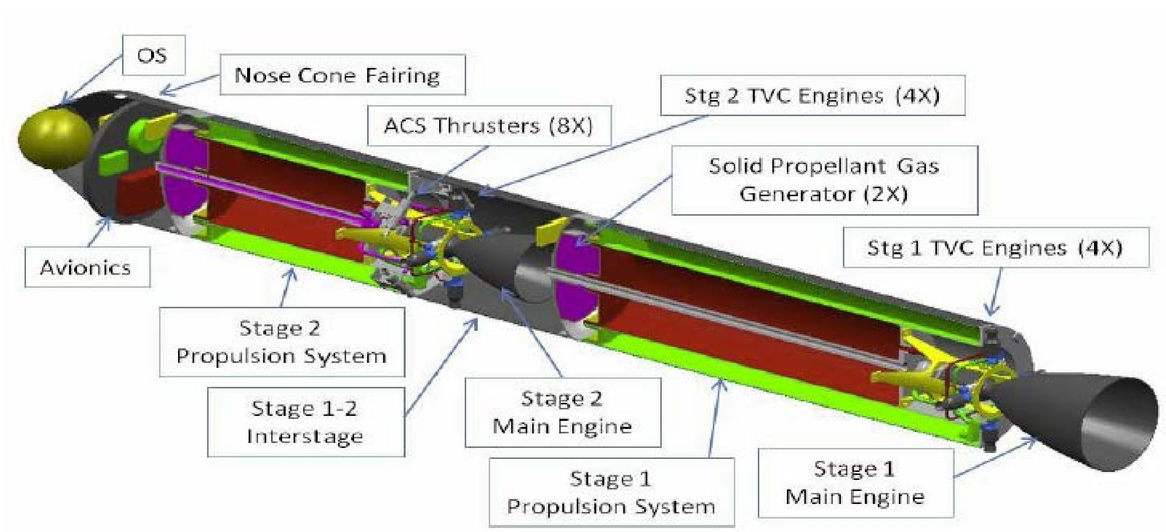


Figure 7. Storable Propellant MAV liquid-liquid concept (NGAS concept)

The key technology challenges for a storable propellant MAV is the ability of the system to withstand the long term storage and delivery to the surface of Mars, the ability to deliver the payload accurately to the intended Mars orbit, and low mass. Meeting these challenges will require a systems engineering approach to balancing MAV performance and reliability. A key element of this will be extensive testing of applicable rocket motors and systems to long term exposure to deep space conditions and Mars surface conditions, and the expected shock, vibration and thermal conditions of the launch and Mars Entry, Descent and Landing (EDL) conditions.

G. Supersonic Inflatable Aerodynamic Decelerators

As the need grows to land more payload on the surface of Mars, the current technologies for Entry, Descent and Landing need to evolve. To some extent, the current technologies for Mars EDL date back to the Viking era: the entry heat shield, disk band gap supersonic parachutes and throttled landing systems were developed to deliver the

Viking landers in the mid-1970's. For MSL, advances in heat shield technologies and the innovative Skycrane landing system have pushed the technology forward, however it still employed the disk band gap parachute which traces back to the Viking technology.

To increase the total delivered mass to the surface for future missions advances in descent technologies are necessary. Supersonic Inflatable Aerodynamic Decelerators (SIADs) and advanced supersonic ringsail parachutes may provide increased landed mass for robotic science and human precursor missions, with Hypersonic Inflatable Aerodynamic Decelerators (HIADs) and Supersonic Retro-Propulsion (SRP) providing more capability for HEO missions. The Low Density Supersonic Decelerator (LDSD) technology project (funded by NASA) is developing a SIAD and the ringsail parachute for infusion for future science missions.

Figure 8 shows current concepts for the LDSD as configured for a robotic mission, and the ringsail concept.

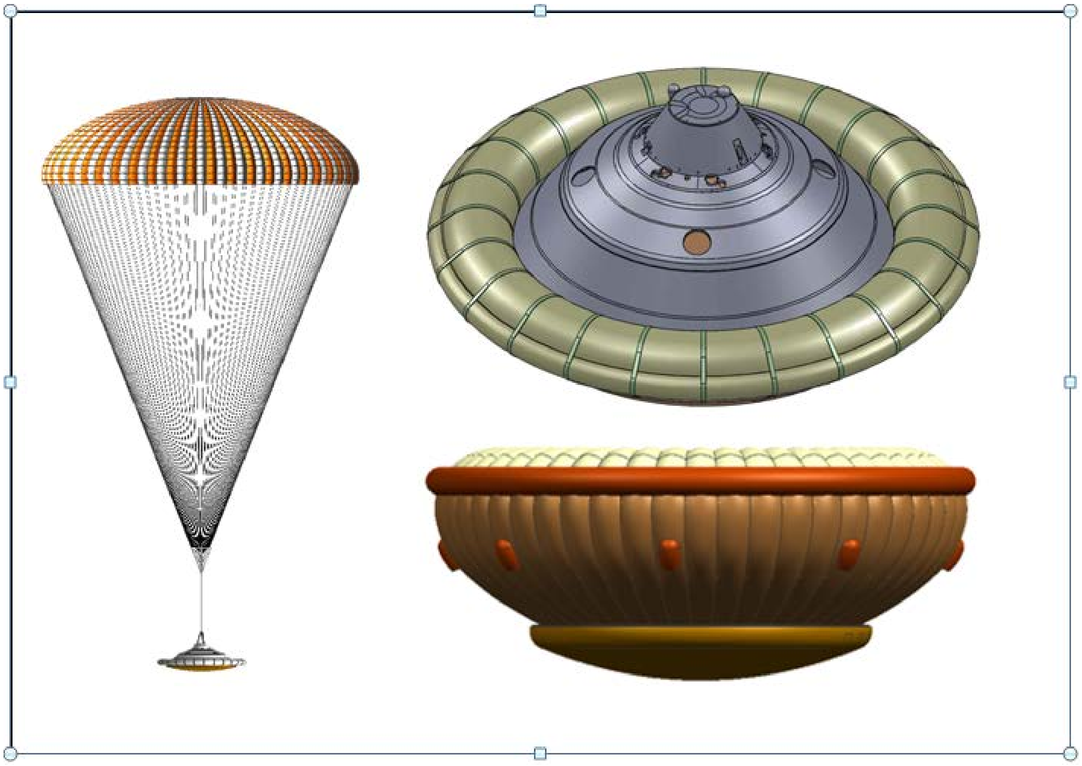


Figure 8. Descent technologies – Supersonic Ringsail Parachute and LDSD

IV. HEO needs that COULD be demonstrated on robotic missions (science or precursor)

Beyond the technologies that are driven by science with application into human exploration, there is a class of technologies that although not explicitly needed for robotic exploration, could be validated on a robotic mission, providing a risk reduction to future human exploration. That risk reduction activity could include full scale technologies or subscale technology demonstrations. Several of the technologies are scalable from their robotic design point to future human needs. Technologies identified in this category are advanced Entry Descent and Landing Systems (EDL), aerocapture, In-Situ Resource Utilization (ISRU) for Oxygen production, ISRU-enabled Mars Ascent Vehicle (MAV), and low gravity operations such as anchoring and mobility.

Advanced EDL technologies include several different concepts, all of which aim to deliver significantly more mass to the surface than the current Mars capability demonstrated by MSL (1 mt). The future human exploration need for payload delivery varies by architecture chosen, but generally the requirement is for 40 mt delivered to the surface[14]. The current approach to Mars EDL, which uses a rigid blunt aeroshell with minimal L/D capability followed by a supersonic parachute, is not extensible to these large landed masses. EDL technologies that can potentially meet this need will be discussed in later sections.

Aerocapture is a technique in which the approaching spacecraft enters the Martian atmosphere and experiences enough drag to decelerate to an acceptable velocity to enter Martian orbit. This maneuver, which has never been demonstrated for a planetary entry, allows for the spacecraft to be captured into a Mars. This parking orbit is ideal for human exploration, in that the spacecraft health can be assessed before entry and the entry sequence can begin once any potentially negative environmental factors have been assessed.

ISRU is an enabling technology for human exploration of Mars. Oxygen generation from the atmosphere alone can support Liquid Oxygen (LO_2) generation for a Mars Ascent Vehicle as well as oxygen production for humans. Current human exploration architectures show that by generating LO_2 on the surface of Mars instead of transporting it from Earth to Mars, the landed mass of the EDL system reduces by approximately 50 percent for an ISRU enabled MAV. This affects the entire architecture, specifically reducing the burden on the EDL system, which already requires a difficult technology development. If ISRU production is expanded to include components of the chosen fuel, then substantial more mass savings can be gained.

V. HEO unique technologies

Certain key technologies are uniquely needed for a human mission to Mars that are not applicable to a science robotic mission. Technologies such as:

1. Closed loop life support systems
2. Deep Space habitation
3. In-flight maintenance techniques for increased self reliance
4. Large scale entry and landing systems
5. Large scale Mars ascent vehicle and propellant production
6. High power for electric propulsion and for surface systems

Advanced closed loop life support systems would significantly reduce the amount of consumables, particularly water and air that would be required for a multi-year long duration mission. This new technology is under development by NASA and could be tested and evaluated in low earth orbit on the on the International Space Station (ISS).

Deep space habitation systems for a long duration mission have multiple and conflicting requirements. To keep the mass down, the size must be constrained. However, the habitation module must accommodate stowage of food and supplies for ≈600 days, crew medical and exercise equipment, radiation shielding, and to accommodate other crew needs, the volume will need to be highly optimized and multi-functional.

For a long duration mission to Mars, far from the safety of the Earth's surface, astronauts will have to rely more on their in-flight maintenance abilities to accomplish their mission. From the ISS, the crew can be back on the surface of the Earth in a few hours should they need to abort their mission. While deep space spacecraft systems will be designed and tested to be highly reliable, sometimes components and systems fail. The experience, techniques and knowledge developed for in flight maintenance of critical flight systems will ultimately allow astronauts to venture further from Earth as they explore the solar system.

In some cases such as for entry and landing systems, ascent and in-situ propellant production systems, subscale tests could be performed at Mars. Other technologies such as advanced life support systems and habitation systems could readily be tested on the International Space Station (ISS) to prove the viability.

VI. Key technologies

The MPPG highlighted two key technology areas that are broadly applicable to Mars exploration missions. The following details the technology areas and approaches for addressing them.

A. Key technologies for Entry, Descent and Landing

Figure 9 details not only the technologies for each phase of Mars entry, descent, and landing, but each technology is classified as fully applicable or potentially applicable to the chosen mission class. Fully applicable means the technology fits within current mission architectures for that mission class. This technology is either required to meet the delivery mass to the surface, or can augment the current capability for the mission class in order to increase delivery mass. The near-term robotic mission class (1-2 mt) encompasses missions done at Mars in the next decade, such as phases of a Mars Sample Return campaign. The Sub-Scale EDL Precursor missions (minimum of 5mt) describe sub-scale human demonstration missions that will be required for risk reduction before a human exploration campaign of Mars is initiated. The EDL architecture chosen for a precursor mission would be dependent on the architecture chosen for future human exploration. The Human Full Scale missions are the class of missions that would deliver crew and cargo to Martian orbit for human exploration.

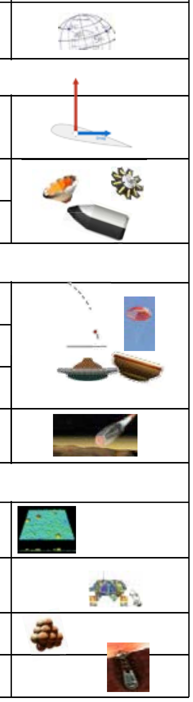
Within EDL, the technologies are broken down into the approach phase followed by technologies specific to entry, descent, and landing phases. During the approach phase, approach navigation was the major technology area identified where applicability to multiple mission classes was identified. Investments in precision star trackers, optical navigation, technologies that provided later navigation updates to spacecraft position, and precision IMU's all provide the capability for greater accuracy in the approach phase. Accuracies in this phase translate to greater accuracy in the EDL phase and smaller landing ellipses upon landing.

The entry phase provided one of the larger investment areas because of the need for the development of advanced hypersonic decelerators. This area is broken down into deployable systems and rigid, slender body aeroshells. Deployable systems, such as a Hypersonic Inflatable Aerodynamic Decelerator (HIAD)[15] and the Adaptable, Deployable Entry Placement Technology[16] provide increased launch packaging efficiencies because the heathsield is stowed until it is needed at Mars. Rigid, slender body aeroshells have a much smaller diameter heatshield, but the increased L/D allows for the spacecraft to remain at high altitudes longer, providing more time for the vehicle to decelerate. Both of these technologies are fully applicable to the Human Full-Scale mission, however only one of them is required. In Figure 9, the "OR" between the two green circles indicates this need for only one eventual technology for the hypersonic entry phase. Neither technology is required for near term robotic missions. Deployable systems are potentially applicable to the robotic missions class missions as an augmentation to the current architecture to increase the mass to the surface. Other technologies that are applicable to all mission classes are lift and drag modulation by reconfiguration of the aerodynamic surface during flight, especially for deployable systems.

During the descent (supersonic) phase is the second major technology area in EDL where a significant investment is required to meet human full-scale mission requirements. Supersonic retro-propulsion represents the only technology that enables 40t human full-scale missions[17]. This technology is potentially applicable to sub-scale precursor missions. Although other EDL technologies can meet the mission requirements, this precursor mission provides a unique opportunity to demonstrate the SRP system required for the full-scale missions. Other key investment areas in this phase are parachute developments and Supersonic Inflatable Aerodyanmic Decelerators (SIAD)[18,19,20]. These two technologies potentially provide a significant mass increase over current MSL delivery capabilities. The 30m supersonic parachute is the first major parachute development for Mars missions since Viking (1970's). These parachute systems are not easily scalable to mission classes above 5t and are therefore not applicable to sub-scale or full-scale human missions. SIAD's are potentially applicable to sub-scale missions as the main EDL system, but are not being looked at as the primary EDL system for full-scale missions. Instead they are being assessed as augmentation devices to the more scalable EDL technologies.

Although the landing phase has a large number of technology areas, the investment required is not as great as other phases. Surface sensing and navigation technologies are the most critical area, with terrain relative navigation and hazard detection and avoidance providing a strong benefit to all mission classes. Storable and cryogenic subsonic propulsion is also an area that enhances all mission classes, providing better performance than other propulsion choices. Energy absorption systems and high-g systems are applicable to near-term robotic missions, but do not scale well to full-scale or even sub-scale human class missions due to the substantial increase in lander mass.

Approach Phase		Near-Term Robotic (1-2t)	Sub-scale EDL Precursor (~5 t +)	Human Full-Scale (20-40t)	
Approach Navigation	Precision Star Tracker, Late Update, Optical Nav, Precision IMU	●	●	●	
Entry Phase					
Atmospheric Guidance	Lift Modulation, Drag Modulation	●	●	●	
Hypersonic Decelerators	Deployables: HIAD, ADEPT	○	○ OR	● OR	
	Rigid: Slender body Aeroshell		●	●	
Descent Phase					
Supersonic Decelerators	Smart Descent/Deploy Logic	●	○	○	
	30m Supersonic Parachute	●			
	SIAD	●	○	○	
Supersonic Retro-propulsion	High-thrust liquid		○	●	
Landing Phase					
Surface sensing and navigation	Terrain Relative Navigation, ALHAT, Hazard Detection and Avoidance	●	●	●	
Subsonic Propulsion	Storable (Monoprop/biprop), Cryo (biprop)	●	●	●	
Energy Absorption	Airbags, Crushables	●			
High-g Systems	Rough Lander	○			



○ Potentially Applicable
● Fully Applicable
Investment Priorities

Figure 9. Key Technologies for Entry, Descent and Landing

B. Key Technologies for ISRU for Mars Ascent

ISRU is an enabling technology for human full- and sub-scale missions because of the substantial propellant mass fraction required for descent and ascent for large human missions[21]. For near-term robotic missions, the propulsion requirement is not as significant. Therefore, the required propellant mass can be delivered with the surface payload without causing significant mass restrictions. The main area within ISRU processing where significant investments are needed is in processing the atmosphere for oxygen. This capability could reduce the lander mass by up to one-half for the current human architectures. Processing the Martian regolith (ice/hydrated mineral processing) for available hydrogen is potentially applicable to both sub- and full-scale missions. The mass savings for creating the fuel is not as substantial as oxygen (although it still is a large mass fraction of the total system), and the amount of available hydrogen in the surface is believed to be substantially less than what is available for processing liquid oxygen from the atmosphere. ISRU-enabled propulsion systems are currently being baselined as LOX/Methane engines. These are classified as "soft" cryogens, which provides substantially easier thermal control than liquid hydrogen. Liquid Methane behaves similar to liquid oxygen, so the long-term storage system would be comparable between the two fuels.

For Mars ascent, performance requirements dictate liquid propellants for human missions. However for robotic Mars missions, there is still a trade between solid versus liquid MAVs. Thermal control of these propulsion systems is fully applicable to all mission classes. The variations in surface temperature at Mars and combined with the long surface stays provide a challenging thermal control problem. Technology investments in this area are critical to any MAV design.

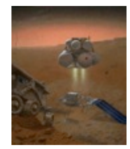
ISRU		Near-Term Robotic	Sub-scale Precursor	Human Full-Scale	
Processing	Atmospheric Processing for Liquid Oxygen		●	●	
	Fuel processing of Surface Available Hydrogen (Ice/Hydrated Mineral Processing)		○	○	
	Other materials – Construction, Radiation Protection		○	○	
Propulsion	LOX/Methane		●	●	
Mars Ascent Vehicle (MAV)		Near-Term Robotic Storable (.2-.3 t)	Sub-scale Precursor ISRU MAV (TBD)	Human Full-scale ISRU MAV (20+ t)	
Propellant Type	Solid vs. Liquid	●	Liquid	Liquid	
Propellant Production	Ox only vs. Ox + Fuel		●	●	
Thermal Control	Isolation from Mars Environment	●	●	●	
Payload Loading	OS Loading, Break-the-Chain	●			

Figure 10. Key Technologies for ISRU and Ascent

VII. Technology Taxonomy and Development / Demonstration Approach

To develop and demonstrate these technologies, a multi-dimensional approach was presented by the MPPG. The approach assumes that some technologies can be demonstrated on Earth, while some technologies must be demonstrated in the relevant Mars environment. For Earth-based demonstration a range of opportunities exist dependent on the necessary conditions to fully verify the capabilities. These range from sub-orbital flights to Beyond Earth Orbit (BEO) demonstration missions.

For those technologies that must be demonstrated in the relevant Mars environment, several approaches are assumed. For some technologies which are amenable to it, deployment as a technology payload on planned science mission may be the most expedient and least costly approach. Payloads in this class could be included as a standalone package with separate demonstration objectives, or could provide non mission critical support to the science mission. Other technologies which are integral to the science mission objectives could be considered, depending on the criticality of the technology to the science goals. However, some technologies may require missions where the primary objectives are demonstration of critical system level capabilities. These missions may consider full scale or sub-scale demonstrations as needed.

For all cases, the selected demonstration method will depend on several factors including cost, complexity and risk reduction goals. Figure 11, presented in the MPPG summary report, illustrates the hierarchical approach to technology demonstration that could be adopted for future science and HEO exploration needs.

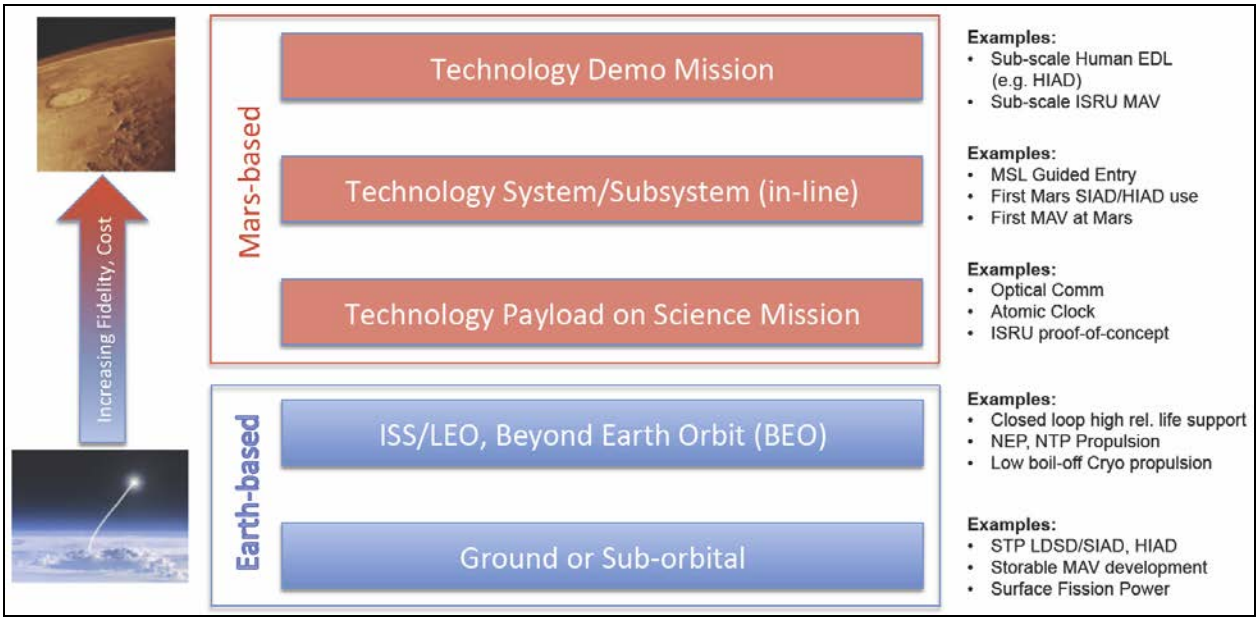


Figure 11. A notional hierarchy for technology demonstration (from MPPG summary report)

VIII. Summary and Conclusions

A summary of critical technology needs to support future Mars scientific and human exploration has been presented. Three distinct technology areas were identified. The first area focused on supporting robotic exploration goals while feeding forward to human exploration. Key technologies in this class were solar electric propulsion, autonomous rendezvous and docking, sample handling and acquisition, atomic clocks, optical communications, storable propellant mars ascent vehicle, and large deployable supersonic decelerators. The second class of technologies identified were human exploration specific needs that could be demonstrated on robotic missions. The two most critical areas identified were advanced EDL technologies and In-SItu Resource Utilization for consumable and propellant production. Both of these technologies are critical for human exploration and fit well within a robotic mission framework for a technology demonstration. The final class of technologies were human exploration specific technologies that are not applicable to science missions. This class included closed loop life support, deep space habitation, in-flight maintenance, large scale entry and landing systems, large scale MAV, and high power for electric propulsion and surface systems. A development and demonstration approach was outlined for the identified technologies, which included Earth and Mars based demonstrations.

IX. Acknowledgements

The authors wish to thank Orlando Figueroa and the members of the MPPG for their contributions to the development of the core technology recommendations and advocacy. Individual contributions by Charles Whetsel, Joe Parrish, Todd Ely and Bret Drake are sincerely appreciated.

Portions of this research were carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration, with contributions from Johnson Space Center (JSC), Glenn Research Center (GRC) and NASA Headquarters.

X. References

[1]Figueroa, O., et al, "Summary of the Final Report", Mars Program Planning Group, NASA Report, September 25, 2012

[2]National Research Council (U.S.). Committee on the Planetary Science Decadal Survey. and National Research Council (U.S.). Space Studies Board. *Vision and Voyages for Planetary Science in the Decade 2013-2022*. Washington, D.C.: National Academies Press, 2011p 6-24

[3]Miller, S. L., J. C. Essmiller and D. W. Beaty. "Mars Deep Drill - a Mission Concept for the Next Decade." In *Space 2004*. San Diego, CA: Pasadena, CA : Jet Propulsion Laboratory, National Aeronautics and Space Administration, 2004., 2004

[4]Kamhawi, H., Manzella, D., Pinero, L., Haag, T., Huang, W., "In-Space Propulsion High Voltage Hall Accelerator Development Project Overview", AIAA-6860, 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Nashville, TN, July, 2010

[5]Hofer, R., "High Specific Impulse Operation of the BPT-4000 Hall Thruster for NASA Science Missions", AIAA-6623, 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Nashville, TN, July, 2010

[6]Zacny, K., Wilson, J., Chu, P., Craft, J., "Prototype Rotary Percussive Drill for the Mars Sample Return Mission", Paper #1125, Conference Proceedings, IEEE Aerospace Conference, Big Sky, MT, March 5-12, 2011

[7]Zacny K., Chu, P., Cohen, J., Paulsen, G., Craft, J., Szwarc, T., "Sample Acquisition and Caching Architecture for the Mars Sample Return Mission", Conference Proceedings, IEEE Aerospace Conference, Big Sky, MT, March 2-9, 2013

[8]Miller, K., Masciarelli, J., Rohrschneider, R., "Advanced is Multi-Mission Autonomous Rendezvous and Docking and Relative Navigation Capabilities", Conference Proceedings, IEEE Aerospace Conference, Big Sky, Mt, 2012

[9]Prestage, J. D., Weaver, G. L., "Atomic Clocks for Deep-Space Navigation and Radio Science", Proceedings of the IEEE, Volume 95, No. 11, November 2007

[10]The National Academies Press, "NASA SPACE TECHNOLOGY ROADMAPS AND PRIORITIES", International Standard Book Number-13: 978-0-309-25362-8, 2012, page 2-24

[11]Biswas, A and Piazolla, S, "Deep Space Optical Communications Downlink Budget from Mars: System Parameters", The Interplanetary Network [IPN] Progress Report 42-154, Jet Propulsion Laboratory, August 15, 2003

[12]Tai, W., Wright, N., Prior, M., Bhasin, K., "NASA Integrated Space Communications Network", AIAA SpaceOps 2010 Conference, Huntsville, Al, April 2010

[13]Dankanich, J. W, Klein, E: "Mars Ascent Vehicle Development Status", Conference Proceedings, IEEE Aerospace Conference, Big Sky, Mt, 2012

[14]Drake, B.G. (editor), "Human Exploration of Mars Design Reference Architecture 5.0", NASA-SP-2009-566, July 2009

[15]Hughes, S., Cheatwood, M., Dillman, R., Wright, S., DelCorso, J., Calomino, A., "Hypersonic Inflatable Decelerator Technology Development Overview", AIAA 20 1 1-2524, 2 1st AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar, 23-26 May 20 1 1, Dublin, Ireland

[16]Yount, B., Prabhu, D., Kruger, C., Gage, P., Squire, T., and Mockelman, J., "Structures and Mechanisms Design Concepts for Adaptive Deployable Entry Placement Technology", AIAA Aerodynamic Decelerator Systems Conference, March 2013, AIAA 2013-1369.

[17]Dwyer Cianciolo, A.M., et al., "Entry, Descent and Landing Systems Analysis Study: Phase 1 Report," NASA–TM–2010–216720, July 2010.

[18]Clark, I., Adler, M., Rivellini, T., "Development and Testing of a New Family of Supersonic Decelerators," 22nd AIAA Aerodynamic Decelerator Systems Conference, March 2013.

[19]Gallon, J., Clark, I., Rivellini, T., Adams, D., Witkowski, A., "Low Density Supersonic Decelerator Parachute Decelerator System," 22nd AIAA Aerodynamic Decelerator Systems Conference, March 2013.

[20]Giersch, L., Rivellini, T., Clark, I., Shook, L., Ware, J., Welch, J., "SIAD-R: A Supersonic Inflatable Aerodynamic Decelerator for Robotic missions to Mars," 22nd AIAA Aerodynamic Decelerator Systems Conference, March 2013.

[21]Sanders, G.B., "In-Situ Resource Utilization on Mars - Update from DRA 5.0 Study", AIAA 2010-799