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Defining the Mars Ascent Problem for Sample Return

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Lifting geology samples off of Mars is both a daunting technical problem for propulsion experts and a cultural challenge for the entire community that plans and implements planetary science missions. The vast majority of science spacecraft require propulsive maneuvers that are similar to what is done routinely with communication satellites, so most needs have been met by adapting hardware and methods from the satellite industry. While it is even possible to reach Earth from the surface of the moon using such traditional technology, ascending from the surface of Mars is beyond proven capability for either solid or liquid propellant rocket technology. Miniature rocket stages for a Mars ascent vehicle would need to be over 80 percent propellant by mass. It is argued that the planetary community faces a steep learning curve toward nontraditional propulsion expertise, in order to successfully accomplish a Mars sample return mission. A cultural shift may be needed to accommodate more technical risk acceptance during the technology development phase.

I. Introduction

Returning geology samples from Mars to Earth has been of scientific interest for decades, ever since the U.S. Apollo and Russian Luna missions returned pieces of the moon circa 1970. In 1976, the historic Viking landers reached Mars, but with no return capability. Expectations for finally accomplishing Mars sample return (MSR) have waxed and waned depending on several factors such as the successes and failures of one-way Mars spacecraft, discoveries and science priorities, technological progress, and anticipated funding. Most recently, MSR has been framed as an international collaboration, with a goal to launch from Earth in 2018.[1]

Beginning with the resurgence of robotic Mars spacecraft in the mid-to-late 1990's, plans took shape to implement MSR within an ongoing, sustainably funded Mars program.[2-4] A new item not common to other space endeavors is the Mars ascent vehicle (MAV), which must lift geology samples to Mars orbit for handoff to an Earth return spacecraft. A variety of liquid propelled and solid propelled MAV concepts was suggested and studied over a period of years, but very little progress has been made toward any implementation.[5-7]

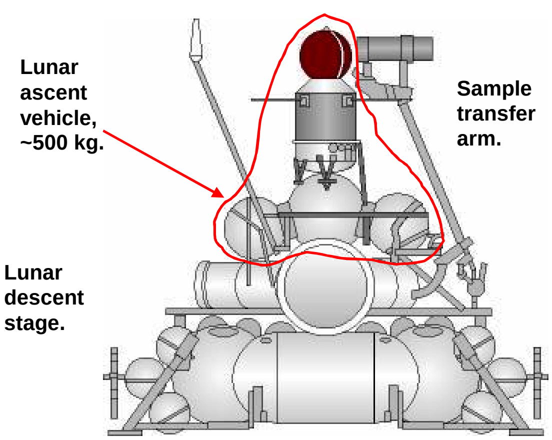

Fig. 1. Configuration for Luna 16, 20, and 24 (c 1970).

Achieving a small size and mass for the MAV is critical to mission affordability, because program budgets have been 1-2 million dollars per kilogram of useful mass landed on Mars. Mission scales will not easily exceed 1 metric ton landed in the foreseeable future, and MAV mass directly displaces instruments for in situ science. The ideal MAV would thus be a couple hundred kilograms, including its support equipment that remains on Mars.

II. Lunar Return History

Owing to the risky nature of space flight, it is always desirable to use proven capability whenever possible. Considering what has already flown, Fig. 1 represents the state of the art for a robotic return of geology samples from a gravitationally significant body. Russian missions Luna 16, 20, and 24 returned

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samples of the moon between 1970 and 1976. The lunar ascent vehicle consisted of a spherical Earth entry capsule atop a cylindrical section containing guidance and communication, both carried by one liquid propulsion stage (note spherical tanks in Fig. 1). The mass at lunar departure was about half a metric ton, heavier than the desired MAV.

An ingeniously unique but mission-constraining solution for navigation was used to simplify both propulsion and guidance for the Luna vehicle's return.[8-9] The missions landed only very close to 56 degrees east longitude near the moon's equator. From there, a purely vertical launch at the correct time and velocity resulted in a direct trajectory to the country of origin. The maneuver was in essence a de-orbit burn with respect to the Earth, as well as a lunar escape. Falling into Earth's gravity meant no midcourse corrections were required, which avoided any need for a propulsion restart. The vertical ascent trajectory permitted the use of a pendulum to actuate vernier engine valves for steering. At that time, a full inertial guidance system would have been prohibitively large and heavy.

III. Mars Ascent Compared to Lunar Ascent

Returning from Mars to Earth presents a greater challenge for both navigation and propulsion. A fully-equipped interplanetary spacecraft is needed, since the trajectory is more than merely falling into a nearby gravity well. It would be extremely costly to take such a spacecraft, with an earth entry capsule, to the surface of Mars and launch it back to Earth as a single vehicle. Prior to meeting the Earth return spacecraft, the MAV must establish a stable orbit around Mars. Doing so still requires some combination of accurate guidance, control, and multiple propulsive events. A circularization burn for orbit insertion would occur many minutes after launch.

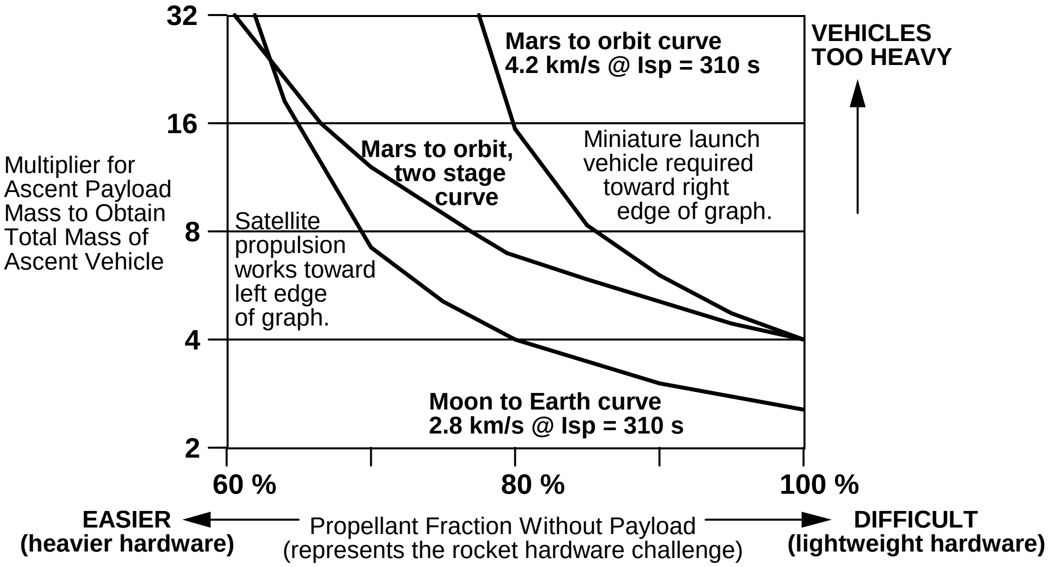

Fig. 2. Mars ascent to orbit is vastly more challenging than a direct lunar return to Earth.

Even though a MAV only needs to reach Mars orbit, the planet's size still requires much more velocity (4.2 km/s) than a lunar return all the way to Earth (2.8 km/s). For these particular cases, Figure 2 illustrates how the launch mass is very sensitive (note vertical log scale) to the propellant fractions of rocket stages. Conventional satellite-type propulsion, used for all planetary spacecraft to date, can readily achieve propellant fractions toward the left side of the graph. Considering the need for directional control and enough thrust to lift against gravity, only multi-ton launch vehicle stages have ever had propellant fractions toward the right side of the graph. Following the curves toward the top of the graph would make any of the return vehicles unduly large and heavy.

The MAV not only needs extremely lightweight propulsion hardware relative to its propellant load, it also should be half or less of the overall mass of the ~500 kg Luna ascent vehicle. In order to put the information in Fig. 2 into perspective, Fig. 3 illustrates example mass allocations for the Luna vehicle and several potential MAV design options. An agreed upon goal for the Mars sample container is about 5 kg. The notional 15-kg MAV payload shown may be interpreted to include avionics, for the convenience of considering stage propellant fractions from a purely propulsion engineering perspective. Comparing MAV options to Luna in Fig. 3, the stage propellant fractions are much higher despite a smaller payload, while the rocket stages must be scaled down. Instead of a moderately sized spacecraft, the MAV must essentially be a miniature launch vehicle.

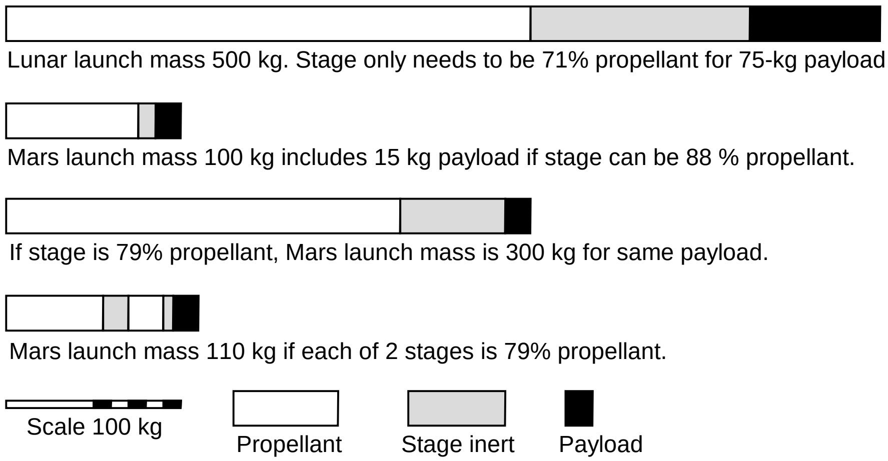

Fig. 3. MAV options need higher propellant fractions than Luna had, despite a smaller payload.

Considering Figs. 2 and 3, it is attractive to consider a two-stage MAV. For a given total launch mass relative to payload, the stage propellant fractions need not be pushed quite so far. However, there is a potential disadvantage of using two stages so the choice is not obvious. An upper stage for a smaller MAV would require not only an additional propulsion development project, it would be a significantly more ambitious miniaturization effort (Fig. 3).

While the information presented here is based on an assumed specific impulse typical of liquid rocket engines, the results for solid propulsion are qualitatively similar. Regardless of the propellant selection or the stage count, aggressive propulsion technology innovation is needed. The above graphs also suggest the need for a serious effort to reduce the mass of MAV avionics, including guidance, control, and telemetry. Considering that the entire mission mass and cost scale as the MAV mass, MSR mission feasibility hinges on the achievable mass of MAV hardware more so than on any other item. Until the technology efforts are undertaken and begin to succeed, the steep curves in Fig. 2 introduce a huge uncertainty into mission design studies.

As a point of reference, state-of-the-art bipropellant rocket engines used for satellite apogee burns typically mass 5 kg and deliver 450 N thrust. This thrust is too low for even a 100-kg MAV, and such engines would use more than a reasonable share of the stage inert masses indicated in Fig. 3. The same can be said for conventional satellite propellant tanks. Propulsion hardware for a MAV must be very different from that which works well for Earth satellites and other planetary missions.

IV. Why Proven Propulsion Usually Works So Well

Space propulsion is a mature technology that has been refined over decades and continues to evolve. Existing capability encompasses both component hardware designs and flight system development methodology. Typically, a new system is designed and assembled from parts that have traceable heritage to previously flown components. Reliability is so high that in most cases it is not even necessary to test a complete propulsion system destined to become part of a satellite or an interplanetary spacecraft.

Table 1 reveals an underlying physical reason why existing technology works so well for many different applications. The actual maneuvers performed by most planetary spacecraft are analogous to those needed for communication satellites. Existing propulsion technology, and advances thereto, are driven mostly by the needs of a

Table 1. Satellite propulsion is adaptable for other planetary flights, because maneuvers are similar.

Satellite Maneuver	Science Maneuver	Maneuver Characteristics
Launch into GTO	Earth escape	High delta V, 1-g accel, large scale
Orbit Maintenance	Course corrections	Low delta V, low acceleration
GTO to GEO	Planet orbit insertion	Moderate delta V, tenth-g accel.
No analogue for:	Planetary ascent	High delta V, 1-g accel., tiny scale

large number of commercial and military satellites. In effect, it has been a lucky coincidence that the propulsive maneuvers required for space science missions typically are similar to what is done routinely for other purposes.

This is not to say that a planetary propulsion system is anything other than highly specialized for its particular purpose. Within the capabilities of the state of the art, modular system methodology works so well that specific new needs are usually met by uniquely combining previously proven component designs or evolved versions thereof.

As noted in Table 1, there is no analogue in the satellite world for the kind of maneuvering characteristics needed to perform a planetary ascent. Considering velocity and acceleration performance together, planetary spacecraft to date have been less capable than the Luna vehicles that successfully launched off the moon.

V. Organizational and Cultural Challenges

The adaptability of mature propulsion technology to the vast majority of science spacecraft has permitted a widespread optimistic expectation. Compared to launching off of Mars, it is straightforward to build other propulsion systems needed for planetary exploration. As a result, there is a significant risk of underestimating the MAV problem, as well as a risk that conventional engineering practice might not even provide a solution.

Table 2 summarizes items of concern, many of which are discussed in detail here. For all these reasons, it is submitted that an unusually steep engineering learning curve will be needed to develop tiny rocket stages for miniature launch vehicles. Possibly, some cultural adjustments will be needed within the wider planetary community. At least patience from the mission planning and Mars science camps will be required. Technical management practices may need to shift toward encouraging innovation, with new flexibility in schedules and budgets that can’t benefit from sufficient foreknowledge in this case.

Regarding technical risk in particular, spacecraft flight propulsion projects typically include a formal process to review and document the flight heritage of selected component designs. Such proven parts include solid propellant rocket motors, as well as liquid tanks, valves, and engines. A high priority is placed on using exact copies of parts previously flown when possible, followed by adapting what already exists. Seasoned professionals in the propulsion field have decades of experience telling customers that needs can be met without significant innovation. For MAV development, such practices could amount to a cultural bias, an inherent aversion to necessary innovation. Certainly, technological risk aversion is a common theme in any spacecraft subsystem development, not just propulsion. Therefore, it is appropriate to consider further issues that are particular to propulsion.

In order to achieve the high propellant fractions and tight mechanical packaging required for a MAV, it is very likely that component designs and the system will have to be worked together as one simultaneous problem. Unplanned iteration of both will almost certainly occur. Conventional methodology for spacecraft propulsion engineering often permits solving component problems and system problems independently. Organizations have been structured accordingly, with separate groups of engineers performing the different functions. For more difficult problems such as the MAV, such separation would be a luxury, loosely analogous to working a crossword puzzle in which the “across” words and the “down” words aren’t constrained by shared letters at intersections.

A simple example, related to mass reduction and packaging of fluid passageways, is the need to decide whether an engine injector should receive propellant tubes axially or from the side. Such a question would not occur for a conventional space propulsion system. Indeed, extra tubes and components are typically welcomed, in order to obtain redundancy for potentially inoperative thrusters, and for flow passageways having valves that might leak.

Table 2. Potential cultural and organizational challenges to consider in MAV development.

• Planetary propulsion has always been less difficult.	• Isolated niche requirement — market forces don't assist — no "technology pipeline."	• Engineering talent pool shift.
• Tradition of risk aversion — demand for mature technology.	• Sensitivity of rockets inhibits open collaboration.	• Low mass not emphasized as a "fundamental" in teaching.
• Rudundancy preference is contrary to MAV mass reality.	• Rockets are hazardous — testing can be very costly.	• Weight reduction taken for granted because it is separate from functionality in other fields.
• Less science glamor for MAV.	• No benign partial failures — MAV must work perfectly.	• Metal and moving parts are considered to be low-tech — specialization "not essential."
• Propulsion industry has been consolidating and shrinking.		
	• More interdependence between component designs and system.	

Unlike imaging sensors, electric power systems, digital electronics, RF communications, and many other items used for planetary science, space propulsion has no related consumer product market. Rocket companies, both solid and liquid, have actually been shrinking and consolidating. Even space propulsion markets generate no need at all, other than Mars ascent, that would lead to or sustain technology, expertise, or specialty organizations for miniature launch vehicles. A primary focus is to extend the orbital lifetime of multi-ton satellites, an entirely different problem from attaining extremely high propellant fractions to depart from planets. Research money designated for innovative propulsion technologies is spent toward evolving traditional satellite components, or newer technologies having extremely low thrust such as electric propulsion.

Consider the community of experts for lightweight imaging sensors. Many different spacecraft programs need them, and an expanding digital camera industry has provided underlying support in the form of new technology, people, and products. If there is going to be a team of specialists focused on miniature launch vehicle development, one has to wonder what these engineers are presently doing to gain the appropriate expertise, and where will their career paths lead to after MAV development? How will such expertise be sustained if the priority to accomplish MSR changes every few years? Of course it is hoped that the existing space and missile propulsion community is the correct reply to these questions, but the discrepancies noted above might require a different answer.

One hopeful notion is that MAV-like solid propellant rockets exist somewhere in the military missile world. However, missiles are designed for quantity manufacture and occasional physical abuse, both of which compromise performance. The small ones, tactical missiles, need to accelerate very quickly and they fly far shorter distances than an orbit-capable vehicle would. Earth's thick atmosphere is relied upon for steering with small fins in most cases. In spite of these differences, the non-public nature of detailed performance specifications lends credence to the possibility that MAV technology lurks behind a veil. Ironically, actual MAV technology, with its vastly different flight profile and a tiny payload, needs to be conservatively treated as militarily significant. Open discussion and international collaboration for MAV development are therefore inhibited.

Ground testing of complete spacecraft and their subsystems is fundamental to ensuring mission functionality. Electrical systems, for example, can be thoroughly tested after final spacecraft assembly, prior to launch. In contrast, propulsion is far more hazardous to test than other spacecraft subsystems, and propellants would need to be reloaded. In order to avoid very costly and time consuming testing, the space propulsion world has settled on ways to ensure system success based on testing of components. Doing so is consistent with the separation of component engineering and system engineering noted above. However, miniature launch vehicle stages will have system level functionality concerns and steering control questions to address by testing whole MAV's on the ground and in flight.

There has been a trend of test facility closures in the rocket world, and those that remain open are tailored for evolutionary changes of proven capability. Many of today's test facilities for space propulsion are both physically and culturally less tolerant of the kind of destructive hardware failures that can occur when pursuing aggressive innovation. Successful MAV development will require not only new lightweight propulsion hardware, but spending that essentially opposes the trend of dwindling test capabilities.

As noted in the third column of Table 2, the broader engineering talent pool has shifted away from building mechanical things having moving metal parts, so there are fewer specialists available. Today's engineering and management culture for spacecraft is heavily influenced by solid-state and electrical expertise. In the broader community, there is even a bias against using moving parts at all. When moving mechanical expertise is needed for spacecraft, it may be practiced as a subset of robotics, which can be dominated by approaches appropriate to electrical engineering and software projects.

Quite often in these latter fields, the mass of hardware is not intimately tied to the underlying functionality. A widespread practice of building a heavy version that is functional, then reducing mass later as a separate activity, has limited utility for solving the MAV problem. Also associated with today's most active and high profile disciplines is the expectation that new emerging technologies will make problems easier to solve at some future date. There is no "pipeline" from which MAV technology will emerge if we wait.

Even among rocket professionals, disciplines such as fluid flow, propellant mixing, and combustion are higher on the list of fundamentals than is the mass of hardware. This bias is partly due to the fact that most rocket development efforts, including university experiments, begin with combustion testing but never progress to the point of building something lightweight.

Finally, regarding perceptions and MAV visibility to the broader planetary exploration community, propulsion is considered to be mere supporting infrastructure. Other mechanical items such as rovers, robot arms, soil scoops, and rock drills are more directly associated with science activities, and therefore receive more attention. References 2 and 4, for example, offer fewer details about the MAV than any other major MSR mission element. How is the grand challenge of MAV development to be sufficiently prioritized and funded, and correctly managed, if rocket technology is not of interest during the decision making process?

VI. The Avionics Challenge for Mars Ascent

Unlike the Russian Luna solution, it will be essential for the MAV design to take full advantage of vast improvements in guidance technology since the 1960's, with an intense focus on miniaturization. It must be appreciated that MAV avionics cannot be just another spacecraft subsystem. The mission mass leverage is roughly an order of magnitude higher than Mars rover electrical systems, for example. A concerted effort to reduce the mass of MAV guidance, control, communication, and data hardware, along with its electrical power system, could easily turn out to be one key mission enabler for MSR.

One avoided kilogram of MAV avionics reduces the total Mars ascent mass allocation by up to 10 kg. Given that recent Mars mission costs have scaled with mass, at roughly $2 million per landed kilogram, each avoided kilogram of MAV avionics is worth perhaps $20 million in mission cost savings. Alternatively, if the mission mass is held constant, an avoided kilogram of MAV avionics could increase the landed science allocation by roughly 10 kg. No other space electronics ever flown would be able to claim an order of magnitude leverage toward enhancing science instrument mass.

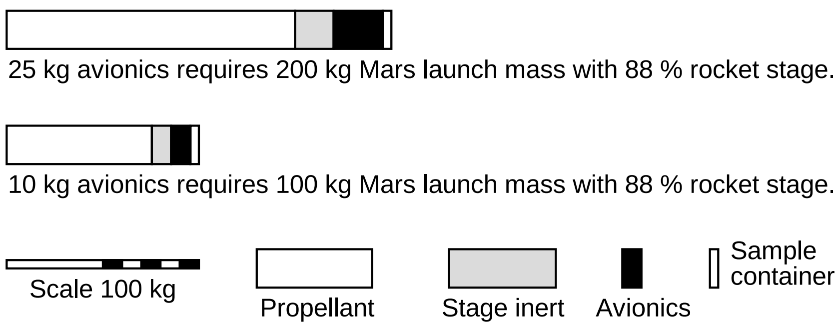

Fig. 4. One example of the effect of reducing avionics mass on the Mars ascent vehicle.

Figure 4 graphically shows an example of the effect of reduced avionics mass. The key point here might not be widely appreciated, because launch vehicles that fly from Earth are generally so large that the mass of their avionics is a very small fraction of stage hardware. When launching a 100-ton vehicle from Earth, it is not a huge problem to include telemetry, cameras, etc. to monitor the functioning of the launch vehicle itself. For Mars ascent, the extent of telemetry for example is a difficult decision that directly impacts overall mission feasibility.

VII. Solid or Liquid Propellant?

As noted in the Introduction, multiple solid and liquid propelled MAV designs have been proposed and analyzed over the past decade and more. Recent papers have offered updated information for particular solid[10] and liquid[11] concepts. Design details are not discussed here, but some key considerations are described, as summarized in Table 3. Each type of system has its own very different challenges, so it is not obvious which would offer a shorter development path to a viable MAV. Both technology options would ideally be pursued.

Solid rocket motors on the scale of interest for a 100-300 kg MAV have existed for decades, and moreover their propellant fractions are very high, near 90 percent. However, it is a huge challenge to turn a bare motor into a complete vehicle stage. A flexible nozzle with steering actuators is needed, if not vanes or attitude control jets. It is not easy to add a directional control system without unduly reducing the propellant mass fraction.

The thrust-to-mass ratio of small solid motors naturally yields about an order of magnitude more thrust than is really needed to launch from Mars.[12] In order to apply correspondingly greater control forces, any directional control system needs to be larger and heavier than would otherwise be necessary for the case of ideal motor thrust. Control bandwidth including both electronics and mechanical actuator responsiveness may need to be increased to obtain sufficiently rapid steering over the course of short motor burn times.

An even more fundamental effect of excessive first stage thrust is that the vehicle would reach high speeds while still low in the atmosphere, resulting in a high aerodynamic drag peak. The aerodynamic fairing covering the nose of the MAV might in turn need to be heavier than for the case of ideal thrust.

Solid propellant contracts at reduced temperatures, which raises the potential for cracks in the propellant grain, or separation from the inner wall of the motor case. In either event, propellant combustion could follow any newly exposed surfaces to change the performance characteristics of the motor. In addition to faster burning of the

Table 3. Technical difficulties relevant to the question of solid or liquid propellant for Mars ascent.

Solid Propellant MAV Challenges	Liquid Propellant MAV Challenges
• Maintain high propellant fractions despite added directional control parts.	• Need all-new propulsion hardware much lighter than satellite parts — engines, tanks, valves, etc.
• High directional control authority with quick action, for high thrust over short burn times.	• Use tanks as vehicle structure.
• Extra delta velocity due to higher aero drag and steeper trajectory, at lower specific impulse than liquid.	• Small short engine nozzles without sacrificing much specific impulse.
• Lightweight nose cone for high peak aerodynamic loads, without heating the sample payload.	• Avoid extra valves traditionally included for redundancy & safety.
• Avoid propellant cracking or wall separation in cold Mars environment.	• Packaging volume for lower density propellant and inert gas.
	• Survive Mars landing loads despite fragile thin tanks.

propellant grain, the detailed performance would be unpredictable and potentially disastrous, such as off-axis thrust as a result of unsymmetrical burning. A solid-propelled MAV would need to be kept continuously heated in an insulated container while waiting on Mars. Reference 10 indicates that 130 watts of average power during storage would need to be raised to 180 watts prior to Mars departure.

Regarding liquid technology, it can be guaranteed that a MAV will not be assembled from flight-proven satellite propulsion components. As noted in the second column of Table 3, a liquid propelled MAV would need entirely new custom propulsion hardware in order to achieve propellant fractions above 80 percent on the scale of interest, with sufficient engine thrust to lift the vehicle from Mars. The ideal thrust-to-mass ratio for a MAV is approximately equal to earth's surface gravitational acceleration, far higher than typical maneuvers performed in space.

Non-wetted structural mass would have to be greatly reduced compared to conventional spacecraft propulsion system practice. In order to utilize tank walls as vehicle structure, and to address the other liquid challenges in Table 3, the author has suggested (e.g. Ref. 11) implementing launch vehicle principles on a very small scale. Such a MAV would consist of low pressure thin-walled tanks, and a high-performance propellant-powered pump[13] to feed compact high-pressure engines. The volume and mass of thick walled vessels for inert gas storage, as typically found on satellites and planetary spacecraft, would be avoided by such an approach.

It would be possible and perhaps very desirable to send the liquid fuel and oxidizer to Mars in separate tanks on the lander. Structural loading on the fragile MAV during Mars descent would be greatly reduced. Personnel safety at the Earth launch site would be assured without heavy and redundant propellant isolation valves on the MAV itself.

VIII. Conclusion

A generalization associated with most transportation technologies is that the capability to return home is a straightforward consequence of being able to go somewhere. However, Mars sample return requires building a launch vehicle that is both capable of departing from a planet, and small enough to send to Mars in the first place. Miniature rocket stages having sufficiently high propellant fractions for Mars ascent do not yet exist, and there is a significant risk that the problem is being underestimated.

The author has encountered a cursory physics analysis to the effect that reducing propulsion hardware mass isn't a critical activity because the propellant itself dominates a vehicle's mass. Such a view is just simplistic enough to be exactly wrong. Similarly worrisome is a widespread notion of engineering that disrespects physical limits, to the effect that anything at all can be accomplished given time, money, and teamwork. The latter is entirely understandable because engineers generally are paid to do work that is destined to be successful, and a positive attitude is a valued attribute of engineering culture.

The mass and size of a Mars ascent vehicle is highly sensitive to the masses of both its rocket hardware and its avionics, with roughly an order of magnitude multiplier. Neither technology exists today in a sufficiently miniaturized form to support a risk-averse Mars sample return flight program on an affordable scale, within anticipated funding constraints that apply to robotic Mars spacecraft. A larger than desired Mars ascent vehicle would either displace landed science instrumentation including rover mass, or it would require increasing the overall mission scale.

It is therefore suggested that sample return mission sizing and cost planning will be premature until aggressive innovation progresses significantly toward building and testing one or more high-leverage miniature launch vehicle technologies. Given the present state of experience and limited activity associated with such technology efforts, ascent propulsion could very well be the one piece of the complicated sample return puzzle that the Mars community as a whole is least prepared to solve.

Acknowledgment

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