Trade Study of Penetration and Sampling Devices for Possible Use on the Mars Sample Return Missions[1]

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Abstract— This paper reviews the work completed on the compilation of a database containing viable penetrating and sampling devices, the performance of a system level trade study comparing selected devices to a set of prescribed parameters and the employment of a metric for the evaluation and ranking of the traded penetration and sampling devices, with respect to possible usage on the 03 and 05 Mars Sample Return missions. The trade study performed is based on a select set of scientific, engineering, programmatic and socio-political criteria. The use of a metric for the various penetration and sampling devices will act to expedite current and future device selection. Three sets of weights and scorings were developed to represent the application of loose requirements, tight requirements and actual conditions. Five alternative lander based sampling system concepts, including the current Mars Sample Return baseline, were evaluated based on the developed criteria and three sets of weights/scorings. It was found that the optimal lander based sampling system for the set of weights/scorings representing actual conditions, was the current Mars Sample Return baseline, due to the no cost condition, from NASA's perspective. However, if this condition is not met, the optimal sampling system may change, based on the selected criteria and weights. This is important in the event that an alternative is required to the current lander based sample acquisition baseline system.

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1. INTRODUCTION

Continuing the 1970's exploration of the Martian surface performed by the duo of Viking landers, is the small armada of missions performed, underway or planned in NASA's Mars Surveyor Program. Two of these missions, with launch dates in 2003 and 2005, are the Mars Sample Return (MSR) missions, which have been tasked with the objective of collecting soil, rock and atmosphere samples from Mars and returning them safely to Earth for in-depth scientific investigation.

Background

The science goals of the Mars Surveyor Program are designed to increase our knowledge on the biologic potential that Mars currently possesses or once had, through the search for various indicators of past or present life. Additionally, a greater understanding of Martian planetary history and evolution is desired. In order to gain access to much of the information that will aid in unraveling these mysteries, the ability to study various samples taken from the atmosphere, surface and subsurface of Mars is required. While previous Mars missions with in situ analysis capabilities and the availability of Mars meteorites has provided much information, the MSR missions will provide relatively pristine samples for in-depth and varied terrestrial based laboratory analysis.

The MSR missions consist of two launches performed in 2003 and 2005. Both launches will contain nearly identical landers, with the second of the two launch opportunities consisting of an orbiter, in addition to, the lander in the payload. Both landers are tasked with providing a means for sample collection and for placing the acquired samples into Mars orbit via the Mars Ascent Vehicle (MAV) for rendezvous with the 05 launched Return Orbiter. After orbital rendezvous, the samples will be returned to Earth late in 2008. In order to accomplish this objective, each lander is equipped with two means of obtaining samples, one based on a rover that is included as part of each lander system and one to be based on the lander platform itself. Sample acquisition and transfer to the MAV is to be accomplished independently by both the rover and the lander based sampling system. Together, these methods are required, over the course of no more than approximately 90 days, to transfer to the MAV a combined cargo of at least 55 soil and rock samples with a combined mass at a minimum of 500 grams, of which approximately 350 grams must be supplied by the lander [1].

Objective and Overview

The primary objective of this study was the identification of potential lander based sample acquisition systems, or simply called sampling systems, and an evaluation of their effectiveness for use on the 03 or 05 MSR missions, in the event that an alternative is required to the current lander based

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sample acquisition baseline system. In accomplishing this, a database of possible sampling techniques and technologies has been complied. From this database, several concepts were chosen and then described at the system level. These sampling systems were subjected to a systems level trade study to identify, compute or estimate and compare the critical parameters of importance to the MSR missions. Lastly, a metric was created by assigning weights to select parameters for the purpose of aiding in the lander sampling system evaluation process so that an optimal sampling system could then be readily identified.

2. TRADE SPACES AND DESIGN OPTIONS

Five sampling system design options were selected from a set of trade spaces that consist of sample types and various sampling techniques and technologies.

Trade Spaces

Two primary trade spaces have been identified and compiled that are applicable when choosing a system that must fit the imposed constraints for use as a lander based sampling system for MSR. These trade spaces contain information concerning possible sample types and sample acquisition techniques and technologies. For ease of presentation, the major areas of each trade space have been summarized and combined to form one, new inter-related trade space, as shown in Table 1a. This trade space is organized by the major categories of sample types that can be collected, by location, and the techniques and technologies that are feasible for sample acquisition in each category. Sample techniques and technologies displayed in the trade space are drawn from a range of terrestrial applications [2], [3] and past planetary lander mission instruments whose purpose was either sample collection or manipulation. Table 1b is a subset of the trade space shown in Table 1a and lists major categories of drilling techniques and technologies, which was identified as necessary for deeper subsurface penetrations. It is noted here that the trade space displayed in Table 1 only details the major sample types and techniques and technologies, while some additional categories not immediately applicable to MSR are not included here. Also displayed in Table 1a are the options of packaging the samples for transport during sampling operations or using an intermediate container transfer, or ICT.

Table 1a is organized by sample type and location, as displayed by the first column. Additional subdivisions of sample type are expressed in the second and third columns, as needed. For example, three methods of obtaining near surface samples were identified, these being: trenching, coring and cuttings. In the trenching and cuttings categories, different design solutions are presented. In the coring category, three additional sub-categories were presented (drilling, impact and core driving) before presenting design solutions. Table 1b is organized in a similar manner, but covers drilling based design solutions. Both tables are related at each point where a drilling design solution is called out in Table 1a. At these points, Table 1b could be substituted back into Table 1a.

To aid in the initial sample type and sampling system down selection process from this trade space, three high level mission drivers were identified and utilized. These drivers relate to, first, limitations on the sample mass that MSR is designed to return, the role of the lander based sampling system to provide a measure of redundancy to the rover based sampling system and, lastly, traditional constraints encountered in all space missions.

Limitations on Sample Return Mass—As the mass allocated to flying the acquired samples to Earth is limited to between 500 and 1000 grams [1], the choice of what types of sample to return should be optimized between scientific value and sampling system feasibility.

Rover Redundancy— In the MSR system level requirements, both the rover and the lander based sampling systems are to provide samples for Earth return, with the lander system providing a larger bulk of the samples. It is desirable that the lander platform possess the ability to provide additional sampling capability over its goal, in the event the rover is unable to complete the sampling potion of its mission.

Space Applications— Like all mechanisms designed for unmanned space flight and operations, the parameters of mass, volume, power, energy, reliability, operational time, automation, etc. are driving factors in system design and selection.

Design Options

Five lander based sampling systems were identified and evaluated for this trade study, including the current 03 MSR lander based sampling system baseline design. Each sampling system can be decomposed into three main subsystems, these being the end effector subsystem, the deployment subsystem and the Sample Transfer Chain (STC).

End Effector Subsystem— The portion of the sampling system that actively acquires and retrieves the samples from the in situ environment is classified as part of the End Effector Subsystem.

Deployment Subsystem— The mechanisms used as the interface between the end effector and the lander platform are grouped into the deployment subsystem. This subsystem also acts as the primary means in which the end effector is moved between sampling locations, deployed from the flight configuration to the operations configuration and also serves to relocate samples into the MAV.

Sample Transfer Chain— The Sample Transfer Chain is defined as the mechanisms and operations necessary to transfer the samples from their in situ environment to Earth. This trade study is only concerned with the mechanisms and

Table 1a: Sample Type and Sample Acquisition Technology/Techniques Trade Space

ATMOSPHERE:	free	trapped					
FREE DUST:	sealed	adhesive	non-ICT	ICT			
SURFACE DUST:	adhesive	non-ICT	ICT				
ROCKS:	Whole	hand	scoop	push	non-ICT	ICT	
	Part	hammer	drilling	non-ICT	ICT		
	Aggregate	scoop	adhesive	non-ICT	ICT		
SOIL:	Pebble	rake	non-ICT	ICT			
	Unconsol.	sieve	adhesive	non-ICT	ICT		
NEAR SURF. (<5 M):	Trench	spade	scoop	non-ICT	ICT		
	Core	*Drilling*	core barrel	doub. barrel	thin wall	remove drill	remv. core
		Impact	remv. mech.	remv. core			
		Core driver	remv. driver	remv. core			
	Cutting	drilling					
SHALLOW(5-200M):	drilling						
DEEP (0.2-4 KM):	drilling						

Table 1b: Drilling Technology/Technique Trade Subspace

MECHANICAL:	Conventional	*Auger*	solid stem	hollow stem			
		Percussive	cable tool	solid rod	hollow rod		
		Rotary	*full-hole*	drag	disc	roller cutter	
				diamond	PCD		
			coring	roller cutter	diamond		
		Rotary-percussive					
	Novel	impact	turbine	explosive	erosion	implosion	
		pellet	spark	sonic	ultrasonic		
HEAT:	Spallation	jet piercing	forced flame	terra-jetter	electric disintegration		
		high freq. elec.	induction	microwave			
	Melting	electric	nuclear	electric arc	plasma	electron beam	laser
	Calcining						
CHEMICAL:	various reactive chemicals						

operations in the STC that enable samples to be collected and deposited into the MAV. Many components of each of the identified sampling systems belong to both the deployment subsystem and the STC.

When choosing the five design options for the trade study, the primary consideration was to provide for a representative set of sample types and subsystems, while still satisfying the three previously identified drivers. The five sampling systems are (named primarily by their end effector): Deedri, scoop, ultrasonic drill, penetrator and monolayer systems.

Deedri— The DEEp DRIll System, or Deedri, is the current baseline lander based sampling system for the MSR 03 mission [4]. This sampling system is being provided by the Italian Space Agency, Agenzia Spaziale Italiana or ASI, and features a system based on an auger drill stem with a Poly-Crystalline Diamond (PCD) bit. Core samples are retrieved with this system down to depths of half a meter. Operationally, Deedri is deployed from the lander and by alternating between drilling and coring, retrieves and individually deposits each core sample into a sample storage cache, which is attached to the system drill box, shown in Figure 1, at the surface. After the sample storage cache has been filled, Deedri is aligned with the MAV where the sample storage cache is then deposited into the MAV.

Scoop System— The scoop system is a modification of the Mars Volatiles and Climate Surveyor (MVACS) Robotic Arm (RA) and scoop end effector being used on the Mars Surveyor 98 and 01 lander missions [5]. This system consists of a two link, four degree of freedom RA that is approximately 2.6 meters long with an actuated scoop located on the end of the arm, as shown in Figure 2. Aggregate soil and small pebble samples are obtained from a relatively large sampling area, where a kinematic depth of 0.8 meters is possible. During operations, the RA is used to deploy and position the scoop to a desired location. There the arm and scoop undergo a series of individual or combined articulations, based on the magnitude of the soil cohesion strength, to dig a trench into the surface. Samples of the material removed from this trench are brought back periodically to the lander based sample storage cache, as shown in Figure 3. Once the cache has been filled, the RA picks up, aligns and deposits the sample storage cache into the MAV.

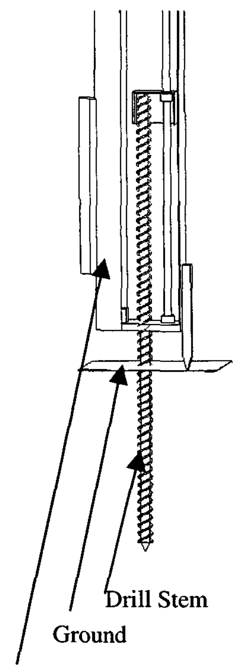


Figure 1: Deedri Drill Box System

Ultrasonic Drill System— The ultrasonic (U.S.) drill is a relatively small end effector that is placed on the end of the RA, which has been previously described. The ultrasonic drill obtains core samples of any material type encountered by employing ultrasonic frequency vibrations, achieving maximum depths of approximately 0.13 meters (~5 inches). The ultrasonic drill's operations are similar to that described in the scoop system section, in that the ultrasonic drill is positioned by the RA, and after penetration, each sample must be returned to the lander based sample storage cache. Once full, the RA must deposit the sample storage cache into the MAV.

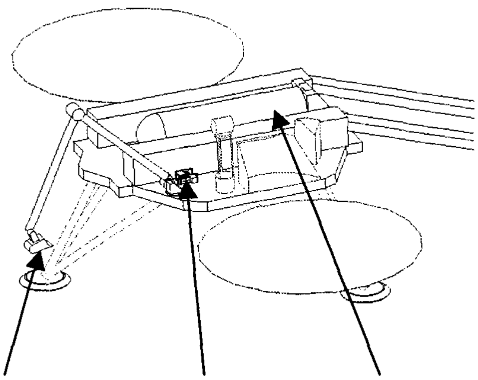


Figure 2: MSR Lander with RA and Scoop End Effector

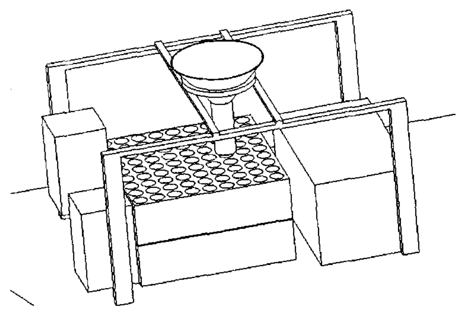


Figure 3: Sample Storage Cache Concept

Penetrators— The penetrator system consists of a combination sample storage cache/end effector at the end of the RA, shown in Figure 4, where room for half of the required penetrators is located. Each penetrator consists of the penetrating barrel, firing charge and a retrieval system, shown in Figure 5. Near surface level core samples are obtained by firing the penetrator into the soil or rock [6] and then retrieving the sample through a reeling system and line attached to each penetrator. Operationally, the RA moves the combination cache/end effector to each sampling location and then deposits the cache into the MAV once all penetrators have been fired and retrieved. The second combination cache/end effector is attached to the RA and this sequence is repeated.

Monolayer— The monolayer system consists of a series of plates that are attached to the end of the RA and have an adhesive applied to one side. These plates can be pressed against the ground to obtain the top layer, or monolayer, of the ground soil, or the surface of a nearby rock to gather settled dust samples or held up freely to collect atmosphere borne dust particles. Operationally, each plate is attached to the RA, used for sampling and then deposited into the MAV. This sequence is repeated until the plate supply has been exhausted.

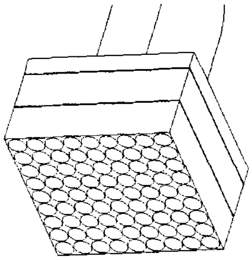
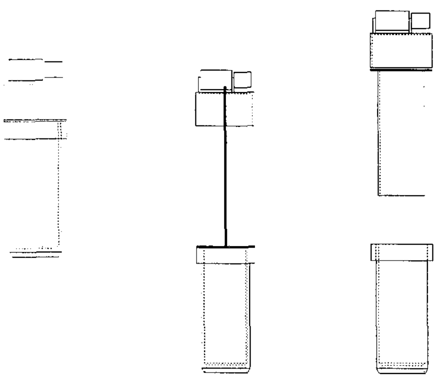


Figure 4: Penetrator Combination Sample Storage Cache and End Effector



(a) (b) (c)

Figure 5: Penetrator Barrel, Firing and Retrieval System, displaying sampling sequence. (a) Pre-fired, (b) Post-fired, barrel in the target, and (c) Post-fired, inner barrel with sample removed from the target, outer barrel remains in the target

3. TRADE STUDY

Over 70 different parameters at the system level, divided over the broad categories of engineering impact, scientific, programmatic and socio-political, were identified. A complete listing of these parameters is located in the Appendix in Table 3. Each parameter was calculated or estimated through order of magnitude calculations, design similarity, packaged software programs or qualitative estimations. As no more that the five most critical parameters in each category were used in the metric creation, to be discussed in the following sections, only those parameters used as criteria will be discussed here.

Engineering

The five critical engineering parameters are familiar for their consistent appearance in space application design, these being: mass, power, energy, volume and operational time. The calculation of the engineering parameters for each design were normalized with respect to what was necessary for each system to achieve either the collection of the required 350 grams of samples or the maximum sample collection mass possible for that system, if less than the required amount.

Scientific

The five critical scientific parameters deal with the anticipated scientific value that the collected samples would possess in meeting the science goals previously stated. The five parameters are: sample type, sample condition, forward contamination, cross contamination and sampling flexibility.

Sample Type— Each sampling system obtains a sample that has an intrinsic scientific value, which is partly a combination of the type and in situ location of the sample. For example, core samples have an intrinsically higher scientific value than dust samples, with respect to the science goals previously defined. Many pieces of geologic information, like stratigraphy for example, are not present or as accurately conveyed with any other sample type than a core sample. Additionally, the ability to sample the subsurface is highly desirable, with deeper being equated to better. This is true even for the ranges of the sampling techniques presented in this study, as samples taken at depths of around 0.5 meters may be deep enough to reach below the oxidizing layer while samples collected at shallower depths will not penetrate this layer.

Sample Condition— To judge the scientific value of the retrieved sample, the condition of the sample must be accounted for, in addition to its type and in situ location. Three separate sub-parameters have been used to determine a sample's condition, which are the maximum center line temperature, and the amount of breakage and compression that the sample would be subjected to during the range of sampling operations.

Forward Contamination— To help maximize the scientific value of the samples during sampling operations, contamination from terrestrial sources should be minimized or eliminated where possible. Possible sources of contamination from terrestrial sources include bio material not removed prior to launch, exhaust from the landers decent rocket engines, or the material used in the sampling system's construction or lubrication. As it is assumed after examination of each of the sampling system concepts that the pre-flight bio burden can be reduced to approximately equal levels, the only parameters that were used in determining a sampling system's susceptibility to forward contamination was the system's ability to work around or negate the effects of the rocket exhaust during descent and the system's material selections.

Cross Contamination— A key factor in deciphering the scientific information present in each of the returned samples is the knowledge of where the sample was located in its in situ environment. Any mixing, or cross contamination, of samples will cloud this knowledge, potentially severely reducing the scientific value of each sample.

Table 2: Sampling System Evaluation Matrix

Criteria		Weights		Deedri	U.S.Drill	Penet.	Scoop	Monolay
Engineering Impact		**30**						
	Mass	35	11	0.0	3.7	4.3	4.2	4.9
	Power	30	9	5.7	0.0	8.3	7.7	8.7
	Energy	15	5	1.2	2.0	4.5	0.0	4.5
	Volume	10	3	0.0	2.1	2.1	2.1	2.1
	Operational Time	10	3	2.0	2.6	2.8	0.0	2.9
Engineering Total				**8.9**	**10.4**	**21.9**	**14.0**	**23.2**
Science		**30**						
	Sample Type	25	8	7.5	3.8	2.3	5.3	0.4
	Sample Condition	25	8	3.8	6.5	6.8	6.0	6.0
	Forward Contamination	20	6	6.0	5.0	5.0	3.0	2.0
	Cross Contamination	15	5	3.0	3.0	4.5	1.5	4.5
	Sampling Flexibility	15	5	3.3	4.5	4.5	3.4	2.4
Science Total				**23.5**	**22.7**	**23.0**	**19.2**	**15.2**
Programmatic		**39**						
	Risk	35	14	9.1	7.2	8.7	9.8	10.9
	Cost	30	12	0.0	2.6	2.8	5.0	4.4
	Total Sample Mass Possible	20	8	7.8	7.8	7.8	7.8	1.4
	Technology Readiness	10	4	3.9	2.6	2.6	3.9	3.9
	Scalability	5	2	1.7	1.8	1.1	1.4	0.6
Programmatic Total				**22.5**	**22.0**	**23.0**	**28.0**	**21.3**
Soci-Political		**1**						
	Terrestrial Application	100	1	**0.7**	**0.7**	**0.6**	**0.1**	**0.1**
Total		100	100	**55.6**	**55.7**	**68.5**	**61.2**	**59.9**

Sampling Flexibility— The sampling system's ability to respond to unanticipated conditions and to be able to offer ground based controllers a choice in sample selection is highly desirable, both from a scientific as well as engineering perspective. A large sampling area and a small sensitivity to local terrain conditions, increases the number of potential samples that can be obtained.

Programmatic

The range of programmatic critical parameters covers issues important to all space missions as well as MSR specific issues. The issues addressed are: risk, cost, total retrieved sample mass, technology readiness and scalability.

Risk— Two components of risk were deemed of interest, these being the risk associated with the sampling system completing it mission and the risk the sampling system posed to the overall lander system. To quantify these areas of risk, a set of sub-criteria, and in some cases sub-sub-criteria were developed and applied to the sampling systems. The area of risk of the sampling system in completing its mission was considered important, as a primary purpose of the MSR mission is the collection and return of samples. As the MSR program level requirements place the responsibility for collecting the bulk of the samples on the lander based sampling system, it is important that both the sampling system hardware and operations perform as designed to help insure compliance with the requirements. As any lander based sampling system must be deployed from the lander, collect samples and transport them back to the lander based MAV, there is a danger that the operation of the sampling system could interfere with or harm the other lander based systems. One such example is the loss of sample containment integrity during transfer to the MAV, in essence, resulting in debris being spilled over the lander's surface.

Cost— As with any space system, cost of each subsystem is an important consideration. This is also true in the Mars Surveyor Program, as each mission, including the MSR, have a tightly constrained budget that must be adhered to. Cost for each model was generated using a commercially available parametric cost analysis software package.

Total Sample Mass— As previously stated, the MSR program level requirements lay out the total sample mass and number of samples that the sampling system is required to successfully collect and transport samples to the MAV. As this requirements is the reason behind the MSR missions, meeting this requirement becomes a driving concern in the choice of sampling system concepts and configurations. Because of this requirement, each of the systems examined were sized so that the minimum required sample mass could be collected. In systems where this requirement could not be satisfied, maximum sample mass that could be collected was calculated. Also, an important consideration in the sample mass collection criteria is the ability of the sampling systems to collect and transport a total mass greater than that specified in the requirements. The sample collection function in the MSR mission is carried out by a lander based and rover based sampling system. One reason for this is to provide redundancy for the sample collection function. If one of the sampling systems should fail, it would be highly desirable for the other sampling system to "make up for" the sample collection mass allotted to the other system, in addition to its own mass collection requirement.

Technology Readiness— As the first set of the two MSR missions has a 2003 launch date, the time remaining between then and the present prohibits the use of sampling systems based on technology that will require a relatively lengthy testing and development program. Technology readiness was based on two factors, current state of the considered technology and the technology's heritage, in terms of systems used on past space exploration missions, terrestrial applications and laboratory state of development.

Scalability— Scalability relates to future use issues in the MSR 05 mission and future missions, primarily expressed in terms of maximum sampling depth achievable. An increase in sampling depth is desirable for several reasons. These can include increased probability for obtaining samples beneath the oxidizing surface layer, additional observation of geologic structure and, at much greater depths, increased possibility of locating liquid water reservoirs and extant life. Other factors can be used for scalability criteria, such as number of samples, sample mass and sample choice flexibility.

Socio-Political

Several parameters associated with the MSR hold the possibility of generating large socio-political interests, such as back contamination or nuclear power sources, but are outside the context of this trade study. The one socio-political parameter evaluated deals with the sampling system's potential for terrestrial applications. Even though commonly employed terrestrial sampling technologies and techniques routinely sample at depths and collect sample masses that are several orders of magnitude greater than that planned for MSR, it is thought that the greatest application of sampling system technology to terrestrial application will come in the form of automation [7]. Any sampling systems used on the MSR will have to be highly automated and possibly even totally self reliant, as human intervention is not possible in real time. As terrestrial sampling operations all require substantial human-machine interaction, the area of automation has been targeted as a critical area of importance by the oil production and service industries. The direct applicability of automation will become even more apparent as envisioned future missions possess sampling systems capable of attaining mueh greater depths than that possible with the systems to be included on the MSR mission.

4. METRIC

In order to provide a means of evaluating the various sampling systems identified, a metric was created [8] by weighting the different parameters and parameter categories. The 16 parameters used as the criteria have already been discussed in the previous section. The weighting values that were chosen are based on the author's knowledge of space mission design, with input on the scientific criteria. Shown in Table 2 are the criteria, weighting factors and scores of each sampling system. High scores represent superior systems, based on the criteria priorities chosen, with a maximum score of 100 possible. As the priorities, and hence the weighting, are changed, the metric created will produce differing results, as shown by example in the following section.

Weighting

As seen in Table 2, a total of 16 criteria were used to evaluate the sampling systems. These 16 criteria were chosen from a total list of over 70 identified parameters. This initial down selection was conducted to create a set of critical criteria less cumbersome that the total criteria set when evaluating the sampling systems. The basis for the critical criteria selection was each criterion's applicability to the overall MSR system. For example, the criteria of mass and power were judged to be more applicable to the overall MSR mission that criteria like hole stability or controllability, which were deemed to be more geared towards a lower level subsystem evaluation. Once the initial criteria down selection was conducted, both the criteria categories and individual criterion were weighted. The choice of weights for each category and individual criterion were selected in an attempt to determine a metric that when used would result in a system that would optimize engineering, scientific, programmatic and socio-political concerns. As is apparent from examining the selected criteria, several of the criterion could potentially be feasibly grouped in multiple categories, though they were restricted to appearing in only one category for this metric, so as not to be overly represented in weight assignments.

Programmatic— Weights assigned to the engineering impact, scientific and programmatic categories were all of the same magnitude, with the programmatic category being ranked 30% higher that either the engineering impact or scientific criteria categories. This additional weight was given to the programmatic criteria to represent the likelihood that criteria like cost and risk can cause the termination of a program, before solutions to more technically oriented problems, like mass or power usage, can be fully explored.

Engineering Impact and Scientific— The set of engineering impact and scientific criteria have both been weighted at the exact same level. This choice was made to demonstrate the rigorous technical constraints that must be met on all Mars Surveyor Program missions, where a reduced scientific return has been accepted, compared to past programs, to facilitate an increase in the number of missions attempted and mission design and development tempo. As the lander mass of the MSR mission is considerably greater that in other Mars Surveyor missions, the relative weights between engineering impact and scientific return is possibly weighted more heavily towards the scientific than previous Mars Surveyor missions, as more resources can be devoted to scientific objectives.

Socio-Political— The weight assigned to the socio-political criteria was assigned a considerably lower number than any of the other criteria categories. The reason for this is that potential drivers of the socio-political criteria, like the use of nuclear power or the possibility of back contamination, were not considered in this study. This was considered valid as current plans for MSR do not allow for nuclear sources [1] of energy and it is assumed that back contamination concerns will be addressed by the portion of the STC that is operationally downstream from the use of the sampling systems. Essentially, this would de-couple back contamination issues from sampling system concepts. The one criterion addressed, terrestrial application, is assumed to play a very small role in the sample system choice and hence had a small weighting factor. The weight was not reduce to zero, however, because future Mars missions are more likely to contain sampling system technologies and techniques that will be applicable to terrestrial application. Also, it is planned in future work to modify this metric for use in evaluating different shallow (<200 m) and deep (down to 4 km) penetration concepts [7], with this category currently serving as a placeholder.

5. RESULTS

After evaluating each of the sampling systems with the selected criteria and weights, the optimal sampling system was the penetrator system, while the system that received the lowest score is the current MSR baseline! From Table 2, it is apparent that the engineering impact criteria was the category where the penetrator system and Deedri received the deciding scores, as their science and programmatic scores were relatively similar. The low engineering score that Deedri obtained was due in part to the higher mass and volume and relatively large power and energy budget that it has. The following discussion is a breakdown of the results for each category, looking briefly at the high and low ranked systems and the penetrator system, which was the overall optimal sampling system.

It should be noted here that the final scores of each system were relatively closely grouped. This type of ranking warrants either a more detailed analysis of the systems, a re-evaluation of the assigned weights or the use of additional criteria, to make an informed decision on which system is optimal.

Engineering Impact— The monolayer sampling system was shown to be the optimal system in terms of engineering impact criteria. This is to be expected as it possesses few complex systems in the end effector system or sample transfer chain, as the end effector is a static structure that doubles as the sample storage cache. By far the lowest engineering impact score was assigned to Deedri, as the forecasted engineering parameter budgets were relatively large, due to the complexity needed in obtaining the deeper core samples. The penetrator system came in a close second behind the monolayer system. As much of the energy needed for the actual sampling procedure is stored in chemical form as explosive charges and the penetration procedure is very fast, low energy and fast operational time are characteristics of the penetrator system.

Science— The high and low scores seen in the science category are reversed from the engineering category. Deedri received the top score for science return, as it returns relatively deep core samples, compared to the samples returned by the monolayer system, which are subject to heavy forward contamination and provide much smaller amounts of geologic, biologic and chemical information. The penetrator system received an average score, as it obtains valuable core samples, but only at very shallow depths.

Programmatic— The scores received by the sampling systems in the programmatic category were all very closely grouped, with the exception of the scoop system. As this system has the greatest heritage of any of the sampling systems because it is a slightly larger scaled version of previous flight tested systems, it scores comparatively high in areas of risk, cost and technology readiness. The lowest programmatic score was received by the monolayer system, due to the fact that it can not meet the sample return mass requirement of 350 grams. It can be argued that as this system can not meet one of the system level requirements, it should be discarded from further consideration.

Socio-Political— In terms of terrestrial application to the drilling and sampling industries, the application of the scoop and monolayer systems was very low, while both Deedri and the ultrasonic drill system receives high ratings. As terrestrial applicability was based on robotic handling, rate of penetration and achievable depth, the robotic handling characteristics of Deedri and the rate of penetration characteristic for the ultrasonic drill make these possible candidates for further study in regards to terrestrial spin off applications. The penetrator system received average scores in this category, as penetrators are already used for certain types of terrestrial sampling.

Variations

An important variation to the evaluation results presented is the assignment of a maximum score to Deedri in the cost category. As Deedri is being provided for use on MSR by ASI, from NASA's perspective it can be considered almost free. With this additional benefit, Deedri is shown to receive a much larger score and practically ties the penetrator system as the optimal sampling system. Another option to consider is the re-weighting of the relative value of the science and engineering scores. As all of the systems presented pose reasonable values in the engineering category, the additional benefits of reduced mass, power, etc. could be reduced in comparison with the science goals. Downgrading the engineering weights to 5% of the total and upgrading science to 55% of the total, results in raising the Deedri system ranking to nearly the top and when combined with the zero cost modifier, it far surpasses the other sampling systems.

The first set of weights discussed corresponds to a set of loose requirements. In this example, the engineering requirements could be assumed to be so nonrestrictive that significant improvements could be obtained between sampling systems in areas such as mass and power consumption. The second set of weights corresponds to a tighter set of imposed requirements, which more accurately describes the MSR situation. In this instance, incremental improvements are minimally advantageous to the system. For example, mass savings on the order of grams would not produce a substantial benefit to the overall system. The last modification, changing the scoring given in the cost category to Deedri to the maximum is meant to represent the actual conditions currently seen in the MSR mission planning. This is from a NASA fiscal reference, as Deedri is being developed for MSR by ASI.

6. SUMMARY

As seen from the Results section, the optimal system that the metric produces is strongly dependent on the choice of criterion priorities. When judging the systems on a balanced weighting of engineering, science and programmatic criteria, the penetrator system appears to be optimal. When taking into account "real world" considerations of no cost to NASA and downgrading the additional engineering benefits for the sake of better science return, then Deedri appears as the optimal system. As the final system selection is highly dependent on weight selection, this metric should not be used blindly, but rather as a tool in assessing strengths and weaknesses of different sampling systems.

Future Work

As many of the science goals identified in the Mars exploration program can only be answered by obtaining samples from depths approaching 4 km, a sampling system capable of attaining such depths is required. The process of analyzing sampling systems for use on the 03 MSR missions should be the start of a broader study of sampling system technologies and mission sequence paths that will be capable of increasingly deep exploration.

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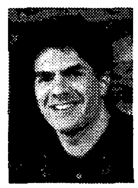

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10. Appendix

Table 3: Complete set of considered parameters

Engineering - Space	Engineering - Penetration	Engineering - Penetration (Continued)	Science
mass	support/retraining force	stuck string	Repeatability
power	power	broken string	sample number
volume	energy	environment	sample size
packagability	torque	cutting storage	sample type(s)
energy	mass	hole diameter	sample catalog (sample location)
support/retraining force	movement	hole depth	contamination (forward, cross)
time	normal force	auto/interactive	return condition/environment (storage/handling)
reliability	sample type	setup/deploy	multi-shot
movement	sample environment	cutting disposal	hole re-sample
robotic operation	cross contamination	sample handling	sample material
flexibility	volume	data recording	sample handling
surface conditions	sample gathering	forward contamination	data recording/transmission
environment	sample removal	back contamination	forward contamination
setup/deploy	wearability	cross contamination	back contamination
cutting disposal	reliability	positioning	sample choice
data recording	multi-shot	surface	orientation
forward contamination	flexibility	subsurface	surface analysis (in situ)
back contamination	resisting torque. force	sampling	
surface positioning	time	removal/take	
entry loads	hole stability	choice	
landing loads	hole re-sample	stability	
orientation	sample material	control	
stability	surface conditions		
control	orientation		
	pressurized gases and fluids		
	formation variation		
	tool replacements		
	proper tool choices		
	problem solving		

Programmatic
mass
volume
power
energy
return
fiscal
time
tech readiness
reliability
scalability (deeper)
heritage (forward and back)
"lego" concept
back contamination

Socio-Political
back contamination
power source
terrestrial application