NEAR-EARTH OBJECT EXTRAVEHICULAR ACTIVITIES: USING APOLLO AND ISS OPERATIONS TO MAP LOW-GRAVITY TERRESTRIAL SPACEWALK OBJECTIVES AND CHALLENGES

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Abstract

The notion of human exploration of a near-Earth object (NEO) is nothing new. Jules Verne wrote about this very idea in his story "Off on a Comet," first published in France in 1877. Since that time, a number of studies have examined NEO exploration for scientific purposes, in-situ resource utilization, mineralogical exploitation and even planetary defense; as early as 1966, a study was conducted to utilize the Apollo program hardware to fly by asteroid Eros 433 [32]. Yet there is very little in the literature archive addressing extra-vehicular activities operations on the surface of a near-Earth object. The arguments for manned missions to near-Earth objects have been presented in a number of papers, recognizing astronauts' adaptability to real-time challenges, the capability to collect geological samples while identifying the overall geological context, and the ability to return a great quantity of those geological samples to Earth, as just a few of the many reasons for a NEO manned mission. Few studies, however, have identified or discussed the myriad challenges of performing surface operations in an environment where the gravitation is considerably less than that of the Moon, but not negligible like the micro-gravity of an International Space Station (ISS) – based EVA. Using the operational experience learned from NASA's various human exploration programs, this paper will identify key challenges unique to NEO surface operations. Furthermore, this paper will map the applicable EVA tasks from both the Apollo program's lunar exploration missions and ISS construction to present an EVA operational concept for NEO surface exploration. Through mapping the applicable Apollo and ISS tasks to the surface of a NEO, relevant operational objectives and challenges are identified, and conceptual approaches to meeting the NEO EVA mission objectives and mitigating key risks are discussed.

1. Introduction

One of the greatest challenges with any manned spaceflight program is defining realistic operational concepts – and thus the hardware to support these operations – early in the program's development. Often the funding and timetable dictate that some sort of basic concept be developed, knowing full well it will need to be iterated throughout the program's lifecycle. This paper will attempt to do a small number of things with respect to extra-vehicular activities (EVA; i.e. spacewalking) operations performed on a near-Earth object (NEO). This paper provides a conceptual roadmap for the development of a NEO EVA architecture drawing upon historical EVA objectives and best practices. First, operational best practices from space shuttle and International Space Station (ISS) EVAs are identified, as well as applicable recommendations made by the Exploration Systems Architecture Study (ESAS) team for the Constellation program [33]. By referencing current operational constraints and best practices, it is possible to establish a meaningful starting point for defining a NEO EVA exploration architecture. Next, the paper will attempt to identify the operational concepts of a NEO EVA by mapping the applicable surface activities performed on the Moon by the Apollo astronauts to a near-Earth object mission. By categorizing the various activities performed on the Moon, this paper will then present the challenges that each category of activity will face when performed on a near-Earth object.

Finally, this paper will discuss mitigation steps for each category of operational risk. One cross-cutting risk that applies to multiple NEO EVA operations, astronaut mobility, will be discussed in detail. By focusing in greater detail upon surface mobility, this paper will then present a number of issues that will require resolution. Furthermore, this paper will demonstrate one simplistic way to address these issues using the ISS as an EVA research facility. Operating in the microgravity vacuum of low-Earth orbit, the ISS provides an exceptional test-bed to validate designs and concepts. This paper will try to present some of the tests that may lead to more effective exploration beyond the Earth-Moon system.

In the 45 years since Alexei Leonov's first extravehicular activity (EVA) of 12 minutes and nine seconds aboard Voskhod 2 on March 18, 1965, people from a multitude of nations have logged hundreds of hours of spacewalk time. Human spacewalking experience, however, can be classified into just two distinct environments: the micro-gravity of space in low-Earth orbit, and the one-sixth-gravity of the lunar surface. [Note: for simplicity this paper will refer to all EVAs conducted in the micro-gravity environment of space as ***orbital*** EVAs, meaning not conducted on the surface of a celestial body.] Currently, the vast majority of spacewalking experience, knowledge and skill has come from orbital EVAs, but this was not always the case.

When Apollo 11 launched to the Moon as the first designated mission to land on its surface, NASA had just 13 hours and 40 minutes of orbital EVA experience, and not a single minute of experience on an extra-terrestrial body. Neil Armstrong and Edwin (Buzz) Aldrin would be forced to rely on their Earth-based training, which was designed to merge the knowledge gained through the orbital EVAs of the Gemini program and Apollo 9 with the low-gravity operational concepts developed specifically for Apollo's lunar surface program. By the time Gene Cernan stepped off the Moon and onto the ladder of the Lunar Module (LM) for the last time on Apollo 17, NASA astronauts had accumulated approximately 161 man-hours of lunar spacewalking experience.

In 1972, NASA had an order of magnitude more hours of EVA experience on the lunar surface than in the micro-gravity environment of space. With the cancellation of the Apollo program, and the subsequent launch of Skylab in 1973, however, it became apparent that expanding EVA capabilities in orbit was essential. The success of Skylab itself hinged on the crews' ability to perform an EVA to repair a solar array that had been damaged during ascent [27]. This event brought the adaptability and utility of EVA to the forefront of mission design.

EVA capabilities for the Space Shuttle program were initially considered only necessary for contingency tasks, yet again its usefulness and flexibility proved invaluable. When the operational concepts for Space Station Freedom were outlined, the space shuttle's payload bay became a proving ground for engineering-based EVA activities. On space shuttle missions like STS-37, flown in April of 1991, astronauts performed planned EVAs to test hardware meant for use on a future space station, allowing the engineers on the ground to gain flight experience [8]. From the knowledge gained through astronaut feedback, designs were altered, concepts were deemed acceptable, and the foundation for the construction of the largest, most complex space system was laid.

This shifted the majority of experience away from lunar EVAs and back to orbital EVAs. The successes of the Hubble Space Telescope servicing missions gave further credibility to EVA, demonstrating the exacting abilities of astronauts garbed in pressurized space suits to perform sensitive, detail-oriented work.

The challenge of the International Space Station (ISS) construction, however, ushered in the ***golden age*** of spacewalking. The assembly of ISS alone has required 134 separate EVAs thus far (as of STS-131/19A completion), with U.S. astronauts dedicating approximately 1,787 man-hours to ISS construction. Over the course of four years, from 1969 to 1972, six separate crews visited the surface of the Moon, conducting a total of 14 EVAs. To contrast this, NASA conducted as many as 23 separate, distinct EVAs in 2002 alone, and matched this number again in 2007 [8].

Yet even after 45 years of spacewalking, the experience is limited to these two environments. There is no doubt, however, that the destinations of the future are beyond low-Earth orbit, and some EVA environments will be beyond the current spacewalking experience-base. Martian gravity, for example, is approximately one-third that of Earth (twice that of the Moon), so it is logical to imagine the operational concept for Mars EVA will be some interpolation of techniques used by the Apollo astronauts on the surface of the Moon and techniques developed here on Earth as part of future mission preparation field tests. Human exploration of Mars however, is likely several decades in the future. In the nearer-term, within the next two decades, near-Earth asteroids represent the next logical step in human exploration beyond the Earth-Moon system.

The question, then, revolves around the types of challenges that will be associated with feasible destinations. Traveling to ***any*** potential target beyond the Earth-Moon system (i.e., a near-Earth object, the moons of Mars, the asteroid belt) will take considerable time. It is essential, therefore, that a manned mission to any such target possess a wide variety of capabilities, to ensure that any operational challenges presented by the uniqueness of the target – from composition, to rotation rate, to varying gravitational fields – do not force the astronauts to abort a mission without exploring the target's surface.

2. An Exploration Strategy

For many, Mars represents the logical next step in human space exploration. The myriad challenges of Martian exploration provide an opportunity for great innovation, but charging forward with Mars as the ultimate goal sets up a repeat of the Apollo program; public interest and government funding tend to wane upon the successful achievement of a seemingly insurmountable goal.

Instead, the exploration strategy must be founded upon a progressive, evolutionary approach, where each new experience adds capabilities to the exploration toolbox. In this way, core competencies do not become destination specific, but are transferable and act only to enhance the exploration architecture.

While human spaceflight currently possesses a unique set of EVA skills, very low-gravity terrestrial exploration will require something more. The construction of the ISS in microgravity was possible only because of the operational considerations included in the design. Translation about the ISS would not be possible without countless handrails along every potential translation path, and assembly would not have been possible without body restraints such as foot plates and the Space Station Remote Manipulator System (SSRMS). Without restraint systems, astronauts would have had no way to react the loads induced, for example, from bolting together truss segments.

The exploration of a very low-gravity body, in contrast, presents nearly all the challenges of microgravity EVA, but without the man-made luxuries that made ISS construction possible. In addition, the EVA tasks of the Apollo program that were relatively simple to perform on the Moon – taking core samples, retrieving surface samples, and even walking – become complicated on the surface of a very low-gravity body. Thus, the current EVA core competencies provide an excellent starting point for the exploration of very low-gravity bodies, but it is apparent that both operational concepts and hardware will need to be developed to explore the vast array of very low-gravity bodies scattered throughout the solar system.

To assist in the development of said operational concepts and hardware, a NEO exploration architecture should utilize robotic precursor missions in conjunction with manned missions, to gain experience incrementally in such areas as target reconnaissance, communication latency, crew autonomy and resource management. To ensure each manned mission is fully prepared, the robotic one-way precursor missions could be sent to any number of NEOs of interest, to determine the characteristics of each NEO – such as its gravitational field, general composition and rotation rate – and to assess whether a specific NEO is a feasible candidate for human exploration [2,17,24]. Incorporating robotic precursor missions into the exploration architecture would mean that a single robotic vehicle design could be the template for a series of missions, utilizing economies-of-scale in searching for NEO candidates by building a number of robotic vehicles from one design, thus reducing the cost per launch.

The exploration of Mars remains a monumental goal, but considering the nearly limitless number of other potential targets for exploration, Mars cannot be the end point of an exploration strategy. Instead, the strategy must develop the EVA core competencies that will allow mankind to explore any terrestrial body. By developing the capabilities to explore such destinations as near-Earth objects and the moons of Mars, destinations beyond Mars – such as main-belt asteroids, and the moons of Jupiter and Saturn – become the potential targets of the future. In this way, Mars becomes a part of the exploration strategy, rather than the final destination of a unique exploration program. And all of this is possible by using NEO exploration as the backbone of an evolutionary exploration architecture that makes each and every destination in the solar system a stepping-stone for the next.

3. Near-Earth Object Selection

The question now being asked is "what constitutes the ***ideal*** near-Earth object for a manned mission?" The response, of course, is that it depends. With the wide variety of near-Earth object types, and the vast majority of the total NEO population yet to even be discovered, much less characterized, it depends on which factors have the greatest influence upon the mission profile. Is scientific exploration the driving factor, or is it bounding the mission duration within a timeframe that reflects current operational expertise? Is it more important to maximize the duration of proximity operations, or to reach the NEO using the smallest possible Δv? Until these questions are definitively answered, any attempt to develop a design reference mission will require it be based upon a large number of assumptions.

To begin to understand the challenges associated with NEO exploration, it is necessary to identify the array of bodies that make up the NEO population, and note the ways in which they are different from one another. This paper cannot begin to capture the diversity of the NEO population as it is currently understood, but will present a sampling of the variations on key characteristics of NEOs to give an appreciation for the challenge of defining and developing a single exploration architecture that can investigate each type of body with adequate capability.

The long-standing definition of a near-Earth objects had been any solar system body (i.e. asteroid or comet) whose orbital elements met the following qualifications: perihelion distance of 1.3 Astronomical Units (AU) or less, and aphelion distance of 0.983 or more [28]. In February of 2003, the Lincoln Near-Earth Asteroid Research (LINEAR) program at MIT's Lincoln Laboratory discovered the first of a new class of near-Earth objects, that of an inner-Earth asteroid (IEA), whose entire orbit is within the Earth's orbit [10]. Since then, according the NASA JPL Small-Body Database (as of May, 2010), nine more IEAs have been discovered, the last of which, asteroid 2008 UL90, was discovered in October of 2008 [38]. Table 1 shows the delineation of the NEO groups, based on the such parameters as perihelion and aphelion distances, orbital period (in the case of near-Earth comets) and semi-major axis.

Group	**Description**	**Definition**
NEC	**N**ear-**E**arth **C**omet	q<1.3 AU, P<200 years
NEA	**N**ear-**E**arth **A**steroid	q<1.3 AU
Atira	NEAs whose orbits are contained entirely within the orbit of the Earth (named after asteroid 163693 Atira).	Q<0.983 AU
Aten	Earth-crossing NEAs with semi-major axes smaller than Earth's (named after asteroid 2062 Atens).	a<1.0 AU Q>0.983 AU
Apollo	Earth-crossing NEAs with semi-major axes larger than Earth's (named after asteroid 1862 Apollo).	a>1.0 AU q<1.017 AU
Amor	Earth-approaching NEAs with orbits exterior to Earth's but interior to Mars' (named after asteroid 1221 Amor).	a>1.0 AU 1.017 < q < 1.3 AU
PHAs	Potentially Hazardous Asteroids: NEAs whose Minimum Orbit Intersection Distance (MOID) with the Earth is 0.05 AU or less and whose absolute magnitude (H) is 22.0 or brighter.	MOID <= 0.05 AU H<=22.0

Table 1. NEO Groups – The vast majority of NEOs are asteroids, referred to as Near-Earth Asteroids (NEA). NEAs are divided into groups according to the perihelion distance (q), aphelion distance (Q) and semi-major axis (a) , and in the case of Near-Earth Comets (NECs), the orbital period (P) [37]

As indicated in Table 1, asteroids make up the majority of the NEO population. As such, much of this paper will often focus on asteroids, in essence using the terms near-Earth object and near-Earth asteroid interchangeably. Near-Earth comets, however, remain viable and desirable targets, but it is likely that any general system that can address the various classes of near-Earth asteroids will have applicability to comet exploration.

Near-Earth asteroid taxonomy places asteroids (and the meteorites that fall to Earth) into three main categories. This categorization is generally accepted throughout the scientific community, but beyond the three main groups, much debate continues regarding how to further delineate the variety of asteroid types that have been discovered thus far. Table 2 below shows the three primary categories, and the types of asteroids found in each category, as defined by Bus and Binzel [5].

Category	Class	General Trait
S-Complex	A, Q, R, K, L, S, Sa, Sk, Sl, Sq, Sr	Silicaceous (stony)
C-Complex	B, C, Cb, Cg, Cgh, Ch,	Carbonaceous
X-Complex	X, Xc, Xe, Xk	Metallic (most often Ni-Fe)

Table 2: Asteroid Taxonomy [5]

C-complex asteroids are believed to be the largest population by percentage, accounting for over one-half of all asteroids. Next would be the S-complex asteroids, and finally the metallic X-complex asteroids, which account for just 7% of the asteroids discovered thus far [5].

Discovering near-Earth objects has become a national endeavor. In 2005, Congress enacted the NASA Authorization Act [1], which stated:

The Administrator [of NASA] *shall plan, develop, and implement a Near-Earth Object Survey program to detect, track, catalogue, and characterize the physical characteristics of near-Earth objects equal to or greater than 140 meters in diameter in order to assess the threat of such near-Earth objects to the Earth. It shall be the goal of the Survey program to achieve 90 percent completion of its near-Earth object catalogue (based on statistically predicted populations of near-Earth objects) within 15 years after the date of the enactment of this Act.*

Thus by 2020, NASA is to have identified and characterized 90 percent of the NEO population, a population which is believed to approach 100,000 individual objects, of which approximately 20,000 could be considered Potentially Hazardous Asteroids (PHAs) [34].

The methods employed are working; the number of known NEOs is constantly growing. Abell et al. noted that, as of September 29, 2009, 6,482 NEOs had been catalogued, including 1,072 PHAs [2]. Just seven months later, and as of May 06, 2010, NASA reports cataloguing 6,918 NEOs, including 1,118 PHAs [37].

As more surveying tools come online, like the Large Synoptic Survey Telescope, being built for deployment to Cerro Pachon in northern Chile, and capable of detecting NEOs within the main asteroid belt as small as 140 meters in less than one minute [39], the known population of near-Earth objects will grow even more rapidly. The LSST is slated to begin construction in 2011 with early scientific operations starting in 2016 [22], and could prove to be a valuable tool to characterize target NEOs, to identify a subset worthy of robotic precursor exploration.

Figure 1 shows the total known NEA population through June 2010. NASA's Near Earth Object Program has catalogued over 7,000 objects, with approximately 800 having a diameter larger than one kilometer. Most significantly, notice the rapid rate of discovery of asteroids with estimated diameters of less than one kilometer, and compare that discovery rate to that of the large NEA category, with estimated diameters of one kilometer or larger. Jedicke et al. suggested that using current surveying methods, 80% of the estimated 1000 large NEAs would be discovered by 2008; this chart supports that hypothesis [13].

Figure 2 shows the distribution of NEA sizes that have been discovered thus far. The largest population of asteroids falls into the 300-meter to 1,000-meter diameter category. However, there are a significant number of large NEAs as well.

Finally, one additional note on target selection. It has been suggested that to avoid the need for significant launch vehicle and spacecraft performance, any NEO that could be considered for exploration should have a very small ecliptic inclination, on the order of 5° or less [3]. As the population of known NEOs grows, this suggested constraint may or may not have a significant impact on target selection and/or vehicle design.

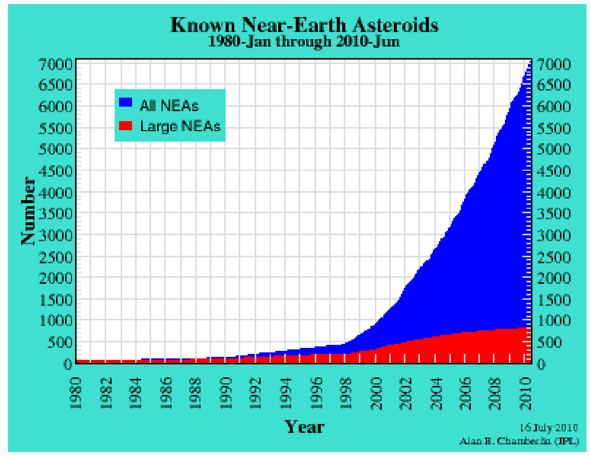

Figure 1. NEA population ("large" is defined as having a diameter greater than one kilometer)[37]

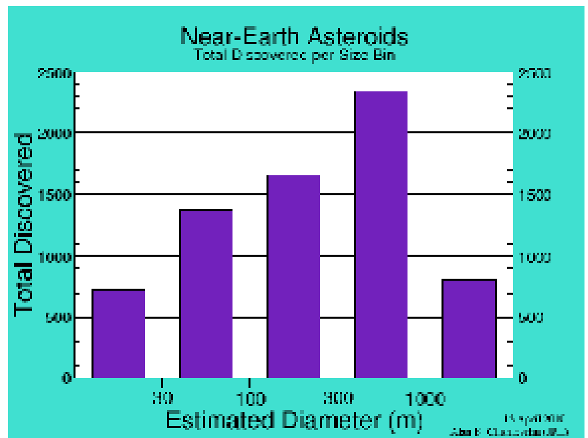

Figure 2. NEA Distribution by Diameter [37]

4. Spacecraft EVA Capabilities

The Apollo program utilized a crew of three to explore the Moon; once in low-lunar orbit, the Commander (CDR) and the Lunar Module Pilot (LMP) would transfer to the Lunar Module (LM), while the Command Module Pilot (CMP) remained behind to man the orbital spacecraft that would bring the crew back to Earth. The LM would separate from the Command Module, and the CDR and LMP would descend to the surface of the Moon.

Once on the lunar surface, the two-person crew would don the Apollo space suits and, over a number of hours, prepare for surface operations. When all systems were *GO* for EVA, the crew would depress the entire pressurized volume of the LM, and once at vacuum, open the hatch, egress onto the porch and descend down the ladder to the lunar surface.

The utilization of an airlock became standard operating procedure for the space shuttle; by having a portion of the vehicle that could be cordoned off and taken to vacuum, the space shuttle could support a two-person EVA while the rest of the crew remained in a shirt-sleeves environment. The ISS operational architecture also followed this approach, dedicating an entire space shuttle mission – STS-104/7A in July, 2001 – to launching and installing the Quest Airlock module, which was attached to the starboard side of the Node 1 Unity module. The Quest Airlock made ISS assembly and operations possible; due to the large habitable volume of the ISS at assembly-complete – approximately 965 cubic meters of pressurized volume (and approximately 400 cubic meters of habitable volume) – the lack of an airlock would render EVA virtually infeasible [25]. In comparison, the portion of the Quest Airlock required to depressurize to vacuum for an EVA is a modest 8.8 cubic meters [6].

The value of possessing airlock capabilities was not lost on mission designers when planning the Constellation program's return to the Moon. To determine the value of an airlock, however, the Exploration Systems Architecture Study (ESAS) team conducted an airlock trade study [33]. Examining a number of airlock variable permutations, the team finally concluded that:

In general, airlocks become more essential as the number of ingress/egress cycles [i.e. EVAs] *increase. The ESAS team concluded that…for 7-day sortie-class accessibility, an airlock is strongly desired; and for an outpost mission, and airlock is essential.*

Figure 3 below shows a depiction of the Lunar Sortie design reference mission for the Constellation program.

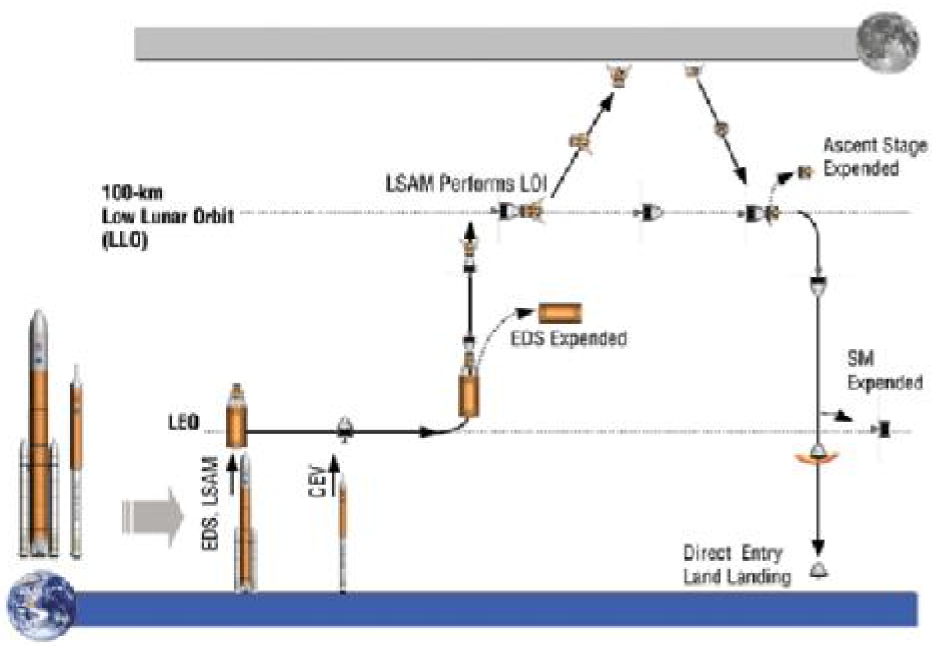

Figure 3 – Constellation Program Lunar Sortie Design Reference Mission [33]

The Constellation program architecture's automation of systems eliminated the need for the Command Module Pilot to remain aloft in low-lunar orbit. For the lunar sortie missions (with a duration on the order of 14 days), the crew complement would be four astronauts, and upon arrival into low-lunar orbit, all four would transfer from the Command Module (CM) to the Lunar Surface Access Module (LSAM), leaving the CM unmanned. The LSAM would undock and descend to the surface, where the crew of four would spend up to seven days completing exploration objectives.

Based on the airlock trade study results, the LSAM would include a bulkhead partition, to segregate a portion of the habitable volume, which could then act as an internal airlock. This would allow the crew to don the Constellation space suits and depressurize just that portion of the pressurized volume to vacuum to facilitate egress. To maximize the value of the lunar surface time, the entire crew of four would have the capability to perform daily EVAs, with all four crewmembers egressing from the airlock together, and working on the surface in pairs.

In comparing a NEO mission to the above programs, it is apparent that the unpredictability of what constitutes the ideal target NEO requires a robust design capable of supporting a wide variety of mission profiles. Crew complement will be discussed in the following section, but regardless of the number of astronauts flown to a near-Earth object, the determination of the ESAS airlock trade study team directly applies; the incorporation of an airlock into the NEO exploration architecture is essential and will provide invaluable flexibility.

5. Crew Complement

The variety of possible destinations discussed thus far demands flexibility in both operations and hardware. By investigating a number of potential target NEOs simultaneously through robotic pre-cursor missions, the baseline design for the crewed vehicle must be capable of supporting the mission profile for any acceptable target NEO. The incorporation of an airlock into the crewed vehicle's design is one crucial way of increasing flexibility. Another is the incorporation of operational constraints for the crewmembers into the initial architecture which directly affect the optimal crew complement.

The EVA lessons learned from the construction of the ISS led to an evolution of operational constraints, termed Crew Scheduling Constraints within NASA. Chief among these EVA operational constraints was the number of EVAs that an individual crewmember could perform over a given period of time.

EVAs on the lunar surface consisted primarily of walking and collecting samples, and eventually traversing greater distances using the Lunar Rover Vehicle (LRV). Suit design led to hand fatigue, but by the time of Apollo 17, crewmembers were routinely hiking up and working on the slopes of craters, all the while maintaining relatively low metabolic rates.

Aboard the ISS, however, complex micro-gravity EVAs demanded more of the crewmembers physically. Fatigue led to inefficiencies, which led to small mistakes. The Shuttle Crew Scheduling Constraints document was developed to capture these lessons learned and formalize them into flight rules, so that a guideline was set and all parties were in agreement regarding the *recommended best practices* for mission operations, including EVA.

The following is the excerpt from NASA's Shuttle Crew Scheduling Constraints [31], along with the rationale of the constraint in italics. This constraint applies for joint missions where the shuttle is visiting the ISS, as well as shuttle-based EVAs such as HST servicing:

- A minimum of one FD [flight day] must separate two scheduled EVAs for any given EVA crewmember.

Rationale: It is overly tiring for the EVA crewmembers to perform an EVA two FDs in a row. To perform consecutive EVAs, two teams of EVA crewmembers must be available.
If an exception request is submitted against this constraint, the following information must be provided for the assessment: the duration of the EVAs, details of the EVA tasks, details and crew workload of other activities on the same mission, and the identity of the EVA crewmembers. Preferably, any request for back-to-back EVAs should be made early enough in the planning process that the crew office can select EVA crewmembers who are experienced and best able to accomplish the objectives. In addition, if multiple EVAs are required, then the back-to-back EVAs should not both be physically intensive. In other words, try to schedule the lighter workload EVAs as the back-to-back sequence. More than two back-to-back EVAs will not be schedule.

For stage increment EVAs aboard the ISS during quiescent operations, NASA's Generic Groundrules Requirements and Constraints places even greater limits on EVA operations [12]. The following is the excerpt, as well as the rationale (again in italics):

- For ISS EMU EVAs, the maximum number of EVA cycles a crewmember should nominally be scheduled for is 2 EVAs per week with at least 2 non-EVA days in between each EVA. However, if, due to a mandatory Station assembly requirement, the Station crew is required to perform 3 EVAs in one week, then this will be allowed.

Rationale: 2 EVAs can be scheduled per week for multiple weeks up to the maximum number allowed per crewmember and suit/airlock consumables (9 per increment [assuming an increment is 180 days in duration] - *reference SSP 50261-01). Time is required for crew rest and EVA replanning between EVAs. However, it is recognized that there may be an exception case where 3 EVAs are required to meet a unique assembly requirement. In this case 3 EVAs in one week are allowed.*

These lessons were not lost on the Constellation Program's ESAS team. As stated earlier, sortie missions to the surface of the Moon planned to allow all four crewmember to conduct EVAs together each day, for up to seven days. In the Executive Summary, it simply states that:

For missions lasting beyond 4 days [on the lunar surface], *a rest day between EVAs may be required.*

Although not as stringent as the wording of the ISS and space shuttle constraints documents, it is also not a groundrule but an indicator that daily surface operations, even in the less physically demanding environment of the lunar surface, is not advisable [33].

Each of these constraints are applicable, in a way, to a NEO mission, as a NEO mission is a blend of them all. Proximity operations will more closely resemble a shuttle mission, with a flurry of activity over a few days to a few weeks. All surface operations will occur during this condensed timeframe, and the constraints learned from the shuttle program are applicable in the very low-gravity of a near-Earth object. However, the transit time to the NEO makes the overall mission more closely resemble an ISS increment, with the crew in the micro-gravity environment of space for months. The constraints for ISS quiescent operations is based on the fact that the crewmembers have been on orbit for an extended duration, and physical fitness is degraded. And surface operations themselves, although in a very low-gravity environment, will have many of the same objectives and challenges that both the Apollo and Constellation programs faced.

Many of the studies thus far typically assume a crew complement of two to three astronauts [7,16,19]. The optimal crew complement is not an arbitrary decision, however, and one of the greatest flexibilities of including an airlock in the crewed vehicle design goes hand-in-hand with the optimal crew complement.

On space shuttle-based EVAs prior to the ISS era, the maneuverability of the shuttle itself served as a method of EVA crewmember rescue. While EVA crewmembers utilized 55-foot long safety tethers when working in the payload bay, the space shuttle's maneuverability was considered the second fault tolerance, should a safety tether fail to keep a crewmember attached to the vehicle. If an EVA crewmember came free of structure and floated "overboard," the space shuttle Commander would maneuver the orbiter into a position where the drifting crewmember would float back into the payload bay. In this way, the astronauts had a secondary method of rescue.

ISS construction, however, required that the space shuttle dock with the orbiting outpost, and the ability to quickly retrieve a free-floating crewmember with the orbiter was no longer possible. To solve this fault-tolerance issue, NASA developed an emergency jetpack, termed the Simplified Aid for EVA Rescue (SAFER), to provide an untethered, free-floating crewmember with a method of self-rescue. A crewmember adrift would deploy a hand controller, use the SAFER first to regain attitude control, and then propel himself slowly back to the ISS.

For both the Apollo and Constellation programs, this issue was of no concern, as the EVA crews were held to the lunar surface under one-sixth-gravity. This meant that the crewmembers exploring the surface of the Moon need only be within walking distance of the LM, should an emergency (a space suit malfunction, for example) arise. Because of this, and the advancements in the automation of systems, the Constellation program had no need to maintain a crewmember in the CM in lunar orbit; the CM would never be used to rescue an EVA crewmember.

As was discussed earlier, however, near-Earth objects rotate. That rotation, combined with the very low-gravity, makes synchronous orbit dependent on great quantities of propellant. Depending on the chosen method of proximity operations at a target NEO, a crewmember may be on the surface of a near-Earth object, out of view of an "orbiting" spacecraft. The weak gravitation limits the mobility of an astronaut – in particular, it limits the speed of an astronaut's mobility – and in an emergency such as a space suit malfunction or a crewmember whose efforts set him adrift from the NEO surface, rescue may rely, as it did for space shuttle-based EVAs, on the spacecraft itself.

For this reason – to maintain flexibility in the methodology of proximity operations, allowing the spacecraft itself to rescue a distressed EVA crewmember – the spacecraft must at all times be manned during EVAs. This precludes a mission complement of two crewmembers, as EVAs are always done in teams of two, and this would leave the vehicle unmanned and incapable of performing a crew rescue.

To examine the optimal configuration, taking into account both the rescue capabilities of the spacecraft and the operational constraints regarding EVA scheduling, Table 3 delineates the permutations of viable EVA crewmembers and airlock configurations for a NEO mission with an arbitrarily chosen ten-day proximity operations mission profile. The maximum scheduled duration for an EVA will be assumed to be six hours and thirty minutes; the rationale for this will be discussed later.

Crew Comp/Airlock Capabilities No. of Scheduling Violations	3Crew/2Person Airlock 0	 1	4Crew/2Person Airlock 0	 1	4Crew/3Person Airlock 0	 1
POD1	EV1/EV2	EV1/EV2	EV1/EV2	NA	EV1/EV2/EV3	EV1/EV2/EV3
POD2	OFF	EV1/EV3	EV3/EV4	NA	OFF	EV1/EV2/EV4
POD3	EV2/EV3	EV2/EV3	EV1/EV2	NA	EV2/EV3/EV4	OFF
POD4	OFF	OFF	EV3/EV4	NA	OFF	EV1/EV3/EV4
POD5	EV1/EV3	EV1/EV2	EV1/EV2	NA	EV1/EV3/EV4	EV2/EV3/EV4
POD6	OFF	EV2/EV3	EV3/EV4	NA	OFF	OFF
POD7	EV1/EV2	OFF	EV1/EV2	NA	EV1/EV2/EV4	EV1/EV2/EV3
POD8	OFF	EV1/EV3	EV3/EV4	NA	OFF	OFF
POD9	EV2/EV3	OFF	EV1/EV2	NA	EV1/EV2/EV3	EV2/EV3/EV4
POD10	OFF	EV1/EV2	EV3/EV4	NA	OFF	OFF
EVA Time Scheduled	32:30	45:30	65:00	NA	32:30	39:00
Man-hours Scheduled	65:00	91:00	130:00	NA	97:30	107:00
EVA Time Possible	65:00	65:00	65:00	NA	65:00	65:00
Man-hours Possible	130:00	130:00	130:00	NA	195:00	195:00
% of Possible Time Spent EVA	**50%**	**70%**	**100%**	NA	**50%**	**60%**
No. of Days w/o EVA	5	3	0	NA	5	4

Table 3. Airlock and Crew Complement for a sample mission with 10 days spent performing proximity operations. Each day at the NEO is identified as Proximity Operations Day X (POD 1 represents Proximity Operations Day 1, the first full day after arriving at a NEO). EV# is the unique identifier for each specific EVA crewmember.

The above example for a mission with ten days of proximity operations indicates that even when allowing for a back-to-back scheduling violation where applicable, no permutation for a three- or four-crewmember complement can match the capabilities of a four-crewmember spacecraft with an airlock designed for two people. This configuration maximizes the number of hours spent performing surface operations (100% of the possible number of EVA hours supportable by the airlock configuration), while having no scheduling violations, and no required days without an EVA. In fact, in this configuration, there is no need to even analyze scheduling violations, because back-to-back EVAs conducted by a single crewmember cannot add any time to the number of hours spent performing surface operations.

Of course, a crew larger than four opens up many more permutations to improve the amount of time spent performing surface operations, but trade studies need to be conducted to determine the benefit of an expanded crew complement versus the changes to vehicle mass, required consumables, and mission delta V, to name just a few impacted parameters.

At the other end of the crew complement spectrum, a mission with much more time at a NEO target may desire days off, and in this case a crew of three may be acceptable. Jones et al. analyzed a crewed mission to 1991 VG in the 1991 to 1992 timeframe, when the asteroid was just 0.004 AU from Earth. The mission profile supported a 60 to 90 day mission, including 30 days performing proximity operations [17]. In this scenario, a crew of three astronauts could support all scientific endeavors with no impacts to operational constraints, because the large number of days performing proximity operations lessens the impact of the required days off.

A significant impact to this such mission profile (or any exploration architecture that counts on a single crewmember being aboard the spacecraft while the others conduct an EVA) that should not be overlooked is with regard to using the spacecraft itself as a method of crew rescue. Since each crewmember would be aboard the vehicle alone at some point, all three must be fully capable of piloting the spacecraft to rescue a stranded or injured EVA crewmember. This would have an impact to pre-mission training (and potentially astronaut selection itself), as a geologist, an astrophysicist, an engineer or a medical doctor (all career categories which currently qualify for astronaut selection), would need to be as adept at flying the spacecraft as the military pilot(s) who would likely be the primary pilots. So while a three-person crew complement is an option for NEO missions with long-duration proximity operations, its inflexibility keeps it from being the optimal choice for a NEO exploration architecture.

Therefore, to maintain the flexibility to explore any NEO assessed by a precursor mission, the nominal crew complement should be no less than ***four*** astronauts, with an airlock designed for use by a two-person EVA team. This requires that only two crewmembers be capable of piloting the spacecraft, and in fact allows the remainder of the crew to be experts in other fields. As was shown with Apollo 17 –

which flew the first scientifically trained Mission Specialist – having geologists (or astrophysicists, engineers or even medical doctors) provides each mission with greater capability. Additionally, a crew of four ensures that surface operations opportunities are maximized, without violating the lessons learned from past flight experience, regardless of whether proximity operations last three or 30 days.

6. Surface Operations – An Overview

The reasons for exploring near-Earth objects – to better understand the formation of the solar system, to advance exploration technologies such as radiation shielding to allow humans to travel farther away from the Earth for longer periods of time, and to develop the capabilities to mitigate potentially hazardous asteroids (PHAs) – has been extensively documented. What is lacking, at this time, is an operational concept of the way in which surface operations will be conducted, and the tasks that will satisfy the above exploration objectives.

One way to create a baseline of EVA activities for near-Earth object exploration is to examine the activities employed by the Apollo program to explore the Moon, and then map those activities to NEO exploration. This can be done effectively in the following manner:

- Categorize the EVA tasks conducted on the Apollo missions that visited the lunar surface.
- Identify the challenges experienced by the Apollo astronauts in conducting each EVA task.
- Map the lunar EVA tasks to the NEO environment and identify the subsequent challenges.
- Propose ways to mitigate those NEO EVA challenges, to meet the NEO exploration objectives.

By utilizing the above methodology, it is possible to create a generalized set of tasks that can then be transposed, or mapped, to the activities that would constitute the backbone of NEO surface operations.

7. Mapping EVA Competencies to a NEO

The disparity between the first lunar EVA on Apollo 11 and the three EVAs of the last lunar mission, Apollo 17, is significant. Apollo 11 conducted a single EVA of 2 hour and 31 minutes, venturing out around the Lunar Module (LM) to perform very basic tasks, such as taking photos, collecting rock samples from the surface and planting the American flag. Compare this to Apollo 17, the first mission flown by a scientist Mission Specialist (geologist Dr. Jack Schmitt). The Apollo 17 mission conducted three EVAs for a total of 22 hours and four minutes, and utilized the Lunar Rover Vehicle (LRV) to traverse approximately 11 km away from the LM on both EVA2 and EVA3. In comparison to Apollo 11, it is apparent that the EVA objectives evolved from simply stepping upon the surface of the Moon to performing true field geology.

And while the complexity grew with each mission, much of the overarching exploration methodology changed very little. In essence, the exploration tasks can be grossly broken down into the following categories:

- EVA preparations (and crew day length)
- Egress and ingress
- Surface mobility
- Scientific experimentation setup (Apollo Lunar Surface Experiments Package (ALSEP) flew on Apollos 12-17, and the modified, lighter-weight Early Apollo Scientific Experiments Package (EASEP) flew on Apollo 11)
- Field Geology
    - Surface Sample Collection:
        - By hand
        - Using tools (tongs, scoop and rake)
    - Trench sample collection using the long-handled scoop
    - Core samples collection using core tubes and the hammer
    - Deep core sample collection using the Apollo Lunar Surface Drill (ALSD) (Apollo 15-17)
- Geological traverse using the LRV (Apollo 15-17)
- Photographic Documentation

Even though this paper focuses primarily on mapping the Apollo lunar activities to a NEO mission, it also incorporates the lessons learned from orbital EVA experience, when those lessons supersede the Apollo experience. The distinct advantage of this approach is that mission designers can use both the experience gained from the Apollo missions and the vast knowledge that has come from the orbital EVAs conducted since then (especially from the expertise achieved through the design and completion of the complex EVA tasks needed for ISS construction). This will be most obvious when examining egress and ingress.

8. EVA Preparation and Crew Day Length

EVA preparation refers to the activities that must be completed prior to the start of an EVA. Depending on the hardware complement flown, tools and space suits may require reconfiguration between EVAs. The operational architecture for a NEO mission should attempt to minimize the amount of time spent between EVAs on hardware reconfiguration, as it can be exceedingly time consuming. If the architecture desires daily EVA capabilities (with alternating 2-person teams, as suggested above), the amount of reconfiguration time each evening after an EVA – in preparation for an EVA the following day – will directly impact the following day's operations, should the crew fall behind the timeline. Thus, whenever practical, hardware quantities (space suits, gloves critical spares, etc.) and operational concepts should be chosen to minimize the frequency of hardware reconfigurations.

To limit the risk of Decompression Sickness (DCS), an EVA preparation prebreathe protocol should be adopted that efficiently purges the body of excess nitrogen in the shortest acceptable duration. For example, when the vehicle's atmospheric pressure is 1 Atm (14.7 pounds per square inch (psi)), the required amount of time spent breathing pure oxygen to purge the body of excess nitrogen is four hours. Conversely, at an atmospheric pressure of 10.2 psi, the oxygen prebreathe duration drops to 40 minutes. Reducing the vehicle's nominal atmospheric pressure even further would reduce the prebreathe duration, but would make the vehicle more susceptible to critical depressurization caused by, for example, a micrometeoroid strike, so a trade study would need to be conducted to define the optimal vehicle atmospheric pressure.

As with all space programs thus far, and because of its relative proximity to the Earth's orbit, a NEO mission will likely operate on a 24-hour clock, to remain in synch with the ground team. In doing so, the amount of time available each day for scheduled activities can be assumed to be a blend of the scheduling constraints of the space shuttle and ISS programs, where it more closely resembles an ISS mission profile during transit to and from a near-Earth object, and resembles a space shuttle mission profile – or even more likely, a space shuttle EVA day profile – throughout NEO proximity operations. Table 4 shows the breakdown of a nominal crew day for both the space shuttle and ISS programs, and an EVA day for a space shuttle mission.

Activity (Hrs)	ISS	Space Shuttle	Space Shuttle EVA Day
Sleep	8.5	8.0	8.0
Post-Sleep	2	3	2.5
Midday Meal	1	1	NA
Exercise	2.5	1.5	NA
Active Duty	6.5	8.0	11.0 • 3.0 Hrs EVA Prep • 6.5 Hrs EVA • 1.5 Hrs EVA Cleanup
Pre-Sleep	2	3.0	2.5

Table 4. Crew Day Length for ISS and Space Shuttle Programs [12,31]

The Shuttle Crew Scheduling Constraints provides the rationale for EVA duration [31]:

- For scheduled and unscheduled EVAs, the planned EVA PET shall not exceed one 6-hour and 30-minute period per day.

Rationale: EVA duration is limited by an EVA crewmember's physical stress, by EMU consumables, and by the crew workday length. EMU primary life support system consumables limit is 7 hours (Reference STS Operational Flight Rules Book All Flights, rule A15.1.1-1 for EMU time limits). Of this 7 hours, 30 minutes is for primary consumables reserve, leaving 6.5 hours for EVA tasks. Oxygen and water supplies can be recharged at vacuum, but the EMU batteries and Lithium Hydroxide (LiOH) canisters cannot. After 6.5 hours of PET the crewmembers will be tired and may experience cold extremities due to reduced circulation in the *suit. In addition, because of all the required pre- and post-EVA activities and the length of the EVA itself, the crew workday will near the maximum limits and should not be extended. With the minimum EMU prebreathe (40 minutes), the minimum required pre- and post-EVA activities, and a 6.5 EVA PET, the crew workday is approximately 11 hours. The standard workday length is 10 hours. Because of the above factors, when using a 10.2 Pounds Per Square Inch (psi) prebreathe protocol, scheduled EVAs are limited to 6.5 hours PET.*

Experience has shown that crew fatigue can lead to errors, and thus the amount of time the crew can work each day is limited. It is therefore prudent to apply the lessons learned from the ISS and space shuttle programs regarding EVA duration and crew day length. For proximity operations, the crew day length should be limited to 11 hours, with a nominal EVA duration limit of six hours and thirty minutes.

9. Airlock Egress and Ingress

The official start time of an EVA aboard the space shuttle or ISS occurs when the first EV crewmember transitions from vehicle power to internal EMU battery power. Within minutes of this transition, the crew completes airlock depressurization and opens the EV hatch. Airlock egress and ingress are thus part of the nominal EVA tasks, and the duration of each needs to be included in the EVA planning, to ensure the 6.5 hour nominal EVA duration is not exceeded. Therefore, even though the various operational concepts may dictate different methods of crew placement onto the NEO surface, translating away from and back to the spacecraft will be considered part of the egress or ingress operations, and thus part of the nominal EVA timeline.

The most significant difference between Apollo and ISS EVAs, with respect to airlock egress and ingress, is the effect of gravity on methodology. Upon opening the hatch on Apollo 11, Armstrong crawled out onto the porch on his hands and knees. His first task was to release the Modular Equipment Stowage Assembly (MESA), which held the sampling tools and sample return containers (SRC), along with the black-and-white camera that would be used to film Armstrong as he stepped onto the surface of the Moon for the first time. He descended the LM ladder to the footpad and using his toe, tested the soil to ensure it was solid enough to bear his weight. When he was confident he would not sink into feet of lunar dust, he made one small step.

An astronaut aboard the ISS does not have as simple a task when leaving the safety of the airlock. The one-sixth gravity of the Moon allowed Armstrong to egress and descend to the surface unencumbered. In the micro-gravity of space, however, an astronaut must utilize tethers to restrain both himself and his tools, lest he find either adrift from the spacecraft.

Prior to opening the hatch aboard the ISS, both crewmembers in the airlock employ a 36-inch long, fixed length tether to connect the EMU to an anchor point inside the airlock. Termed a waist tether because it connects to a D-ring on the waist of the EMU, the waist tether has a hook at each end and is used to ensure that a crewmember does not drift away from structure should he let go with both hands to complete a task. Once the hatch is opened, the first crewmember egresses the airlock. Once outside, he attaches the anchor hook of another tether, this one termed a safety tether, to an anchor point on the outside of the airlock. This safety tether is also attached to the EMU D-ring, but rather than being a fixed length, this tether is 85 feet long and made of a 3/32” braided stainless steel cable. The cable is wound around a spool in an enclosed reel, and is designed to tend out as the crewmember translates away from the anchor point, and retract (with a very low spring force) as the crewmember translates back toward the anchor point. In this way, the crewmember is always attached via a cable to the spacecraft, such that should he become physically separated from structure, he still has one life-line to keep him from becoming a human satellite.

Herein lies the drastic difference between a lunar EVA and an orbital EVA; with even one-sixth gravity, an Apollo astronaut did not need to worry about floating away from the lunar surface. He was able to translate on the surface without being tied to the LM, and in later missions it gave the Apollo astronauts the freedom to travel and explore many kilometers from the LM. For a NEO mission, the gravitational field will be stronger than the micro-gravity of space, but tethering protocols will still be required. Depending on the gravitation of a target NEO, it may even be possible for an astronaut to impart enough force to reach escape velocity. Therefore, a NEO astronaut will need to remain tethered at all times. This adds considerable complexity to a

NEO EVA over an Apollo EVA, and may even play a more restricting role than aboard the ISS.

9.1 Tether Protocol – NEO “Landing”

If the spacecraft is capable of “landing” and grappling onto the NEO’s surface, the crewmembers could use a tethering protocol similar to that used aboard the ISS, where the safety tether is anchored directly to the spacecraft. This would allow the astronauts to maintain a lifeline to the spacecraft, ensuring the ability to quickly return to the airlock in a contingency scenario that required an expedited ingress.

9.2 Tether Protocol – NEO “Mooring”

If the spacecraft can moor to the NEO and remain directly overhead, the crew can employ a similar tether protocol, but instead of tethering to the spacecraft, the astronauts would tether to the mooring line. The space shuttle and ISS both utilized slide wires to aid in translation about the respective vehicles. By attaching the anchor hook of the safety tether to the slide wire, the tether gained a degree of freedom; the anchor hook was able to slide along the length of the slide wire, providing extended range. In the case of the space shuttle, the slide wire ran the length of the payload bay and gave a crewmember the ability to translate the payload bay’s full length without extending the safety tether.

If a mooring line is employed at a NEO, the slide wire concept can be transposed to the mooring line. Upon airlock egress, an astronaut would attach his safety tether to a slider on the mooring line and descend under his own power along the mooring line to the surface of the NEO.

This poses advantages and disadvantages. The primary advantage mirrors that of being tethered directly to the spacecraft: in an emergency, an astronaut has a lifeline (made up, in this case, of the safety tether to the mooring line, and the mooring line to the spacecraft) to follow back to the airlock. Additionally, as mentioned earlier, any mooring line has the potential to break free of the surface. Should this happen, the crewmembers are tethered to the mooring line, ensuring that the crewmembers possess the lifeline to the spacecraft even if the spacecraft is no longer in contact with the surface.

The obvious disadvantage is that the crewmembers are tethered to the mooring line should it break free of the surface. If the spacecraft drifts from its position after a failure of the mooring anchor, it has the potential to pull the crewmembers across the surface of the NEO, which could be detrimental to the pressurized spacesuits, or it could pull the crewmembers completely off the surface, which could cause the astronauts to tumble and become wrapped in their safety tethers. Adrift in free space, tangled in a safety tether, an astronaut would be in a precarious position without the aid of his EV partner.

Due to the great risk of being dragged across the surface of a near-Earth object covered in jagged rocks, this method is not recommended. If the spacecraft’s proximity operations dictate a mooring method, it is advisable to devise a method to decouple the crewmembers’ safety tethers from the mooring line by a separate, crewmember-installed anchor that is set into the NEO itself once the astronauts reach the surface. The crewmembers can then swap the safety tether anchor point from the mooring line to this newly-installed safety tether surface anchor.

Such an anchoring system has its own inherent risks, however, that cannot be overlooked. Should the mooring line break free, there is no direct path to the spacecraft’s airlock for an astronaut in an emergency. This would likely dictate that the crewmembers be outfitted with an emergency mobility unit similar to the Simplified Aid for EVA Rescue (SAFER) that is employed aboard the ISS. The SAFER mounts to the bottom of the EMU PLSS and has a deployable hand controller module (HCM) to allow the crewmember to steer himself back to structure if circumstances put him in free space.

This scenario would be less likely, however, as it is two failures deep. First it is dependent on a failure of the mooring anchor, and then simultaneously on a suit or hardware failure that requires an expedited ingress. Should the mooring line anchor fail, the crewmembers aboard the spacecraft would nominally act to set the mooring line again, and at the completion of the EVA, the EV crewmembers would translate to the reset mooring line and ascend to the airlock.

9.3 Tether Protocol – NEO "High Hover"

In a high hover proximity operations concept, the spacecraft cannot "land" or moor to the surface of the NEO, and must instead simply position itself in proximity to the NEO. During airlock depressurization, the spacecraft would lower its relative altitude to approach the NEO, and upon egress, the crewmembers would have to traverse across free space to the surface using a propulsive mobility unit.

This operational concept provides the greatest flexibility regarding the choice of targets; by eliminating the need for the vehicle to come into contact with the surface, the size, shape, physical composition and rotation rate have less influence over proximity operations in general terms. Varying gravitational fields and overall shape will dictate how close the spacecraft can approach the surface, but with the capability to traverse free space, the EV crewmembers provide human-in-the-loop flexibility to viable proximity-operation methodologies.

The greatest challenge for the EV crewmembers will be descending to the surface with an angular velocity that matches the NEO's rotation rate. Without precisely matching angular velocities, the EV crewmember will either approach too slowly or too quickly, resulting in the relative motion making the crewmember feel as though he is skidding across the surface. Because of the limited weathering of the NEO surface, there is great risk of damage to the spacesuit from jagged rocks strewn across the surface of the NEO.

This can be mitigated by flying the spacecraft in a synchronous orbit of the NEO during egress, so that the initial motion of the EV crew is in synchronicity with the surface. A crewmember can then use the propulsive mobility unit to descend to the surface, tweaking the angular velocity to settle onto the surface with zero relative angular velocity. This operational concept would require two constraints be met. First, from a propulsion perspective, the vehicle would have to be capable of flying multiple synchronous orbits, to allow as many EVAs to be performed as possible for a specific mission profile. Second, the propulsive mobility unit used by the EV crewmembers would have to be significantly more capable than the SAFER. The SAFER was designed for contingency use only, and is propellant limited. A propulsive mobility unit, used as described above, would be employed as part of the nominal operations, and thus would need a capability (and thus a propellant storage and refueling system) significantly greater than the SAFER, to ensure nominal usage over the course of an EVA, with reserves for contingency operations.

Similarly, by selecting a target NEO with a single axis of rotation, a polar approach can limit the effects of rotation rate on crewmembers as they descend to the surface. Positioned over the pole, the crewmembers can traverse free space in the same manner as above, but the smaller starting relative angular velocity will place less demand on the propulsive mobility unit as the crewmember approaches the surface with zero relative angular velocity. The greatest disadvantage of utilizing a polar approach profile is that it limits the exploration area to that around the pole, making areas of interest near, say, the equator, much more difficult to investigate.

The distinct disadvantage to relying primarily on a propulsive mobility unit – whether it be simply to traverse to the surface, or to act as the primary mode of surface mobility – is the way in which it will interact with the NEO environment. Typically such systems employ cold-gas thrusters, oriented along all three axes to provide not only propulsion, but attitude control. Should the surface of a target NEO be inundated with dust, the plume of cold-gas thrusters could create white-out conditions, similar to disturbing the silt while scuba diving. With very low-gravity, the dust will not quickly settle, and repeated jet firings could exacerbate the problem, possibly making it impossible for an astronaut to maintain situational or spatial awareness. The information gained from a robotic precursor mission will help classify the dust content, but building an exploration architecture around thrusters as the primary mode of mobility may severely limit the number of acceptable destinations.

9.4 Open Work

The wide variety of near-Earth objects dictates that any single method is not likely to support mission operations at all targets of interest. One way to combine "landing" and "mooring" methods together, for example, may be to use a variable length mooring line: whether using a physical or chemical anchoring system, the variable length line could be retracted to place the vehicle onto the surface of the NEO, if desired, or allow it to reel out and remain farther from the surface. As the ability to classify near-Earth object surface composition improves (from land-based or space-based observatories, or from robotic scout missions), anchoring methods can be chosen and optimized, but until there is more hard data, a slew of techniques based off loose assumptions will need to be developed, tested and added to the toolbox of capabilities for NEO exploration.

10. Surface Mobility

One of the greatest challenges to low-gravity body exploration will be to develop ways to translate across the surfaces of the various bodies, each with its own unique gravitational field. The largest NEO, 1036 Ganymed, has a diameter of 31.66 km, and it is significantly larger than the next largest NEO, 433 Eros, which has a mean diameter of 16.84 km. Compare the size of these objects to 2010 RF12, which has an estimated diameter of six to 14 meters, and passed within approximately 79,000 kilometers of Earth in September of 2010, and one can see the vast array of objects which exist under the NEO moniker [38].

Due to this great disparity in the size of potential targets, an exploration architecture must possess the capabilities to explore a low-gravity body with a diameter, for example, of just 200 meters, and one as big as 1036 Ganymed, in an equally effective manner. Add in main-belt asteroids and the moons of the gas giants to the low-gravity body population, and the list of potential targets is nearly limitless.

As mentioned earlier, a potential target may be attractive because of its size, composition, distance from Earth, rotation rate, or various other parameters. Yet this vast population, along with the various classes of these objects, implies the inability to create a "one-size-fits-all" exploration architecture for very low-gravity bodies.

A starting point, however, must be chosen. For the purposes of this paper, the potential target of choice represents a viable mission target, even if the exploration architecture of the future chooses to steer away from near-Earth objects. Because Mars will always remain a high-value target, this paper will use Phobos, one of the two Martian satellites, as the representation of a very low-gravity body for a surface mobility analysis.

Phobos is larger than all but one NEO, but easily fits within the range of very low-gravity bodies that will require new EVA tactics for exploration. Additionally, there has been a considerable amount of work done to characterize Phobos – mean diameter, rotation rate, and bulk density are all measured quantities – making an analysis more accurate. Figure 4 is an image of Phobos taken from NASA's Mars Reconnaissance Orbiter on March 23, 2008 [20].

Figure 4. MRO image of Phobos[20]

10.1 Phobos Properties and Assumptions

This paper will model Phobos as a sphere with constant bulk density, rotating about a single axis. This allows a simpler calculation of the gravitational acceleration at the surface. Inconsistent bulk densities or non-spherical shapes alter the site-specific surface acceleration due to gravity, introducing further challenges to an astronaut attempting to traverse across the surface. Table 5 presents the parameters of Phobos relevant for this analysis.

Parameter	Symbol	Value
Gravitational Parameter	GM	$0.7127 \pm 0.0021 \times 10^{-3}$ km^3/s^2 [4]
Bulk Density	ρ	1876 ± 20 kg/m^3 [4]
Porosity		30% ± 5% [4]
Mean Radius	R	11.1 ± 0.15 km [37]
Period	P	0.3189 days [37]

Table 5. Phobos: given properties (note that G represents the gravitational constant and equals 6.6725×10^{-20} km^3/kg/ s^2)

The gravitational acceleration will then be calculated by:

$$g = -\frac{GM}{R^2} \quad (1)$$

yielding a surface gravitation value of 5.784 x 10^{-3} m/s^2 acting toward the center of Phobos. To calculate the total surface acceleration, however, the gravitational acceleration must be summed with the centripetal acceleration caused by the rotation rate, acting opposite the gravitational acceleration.

$$g_{TOT} = (\omega^2 cos^2 \delta)R - \frac{GM}{R^2} \quad (2)$$

where ω is the rotation rate, in rad/s, and δ is the latitude (measured from the equator). The greatest value for $cos^2 \delta$ (and thus the greatest effect that centripetal acceleration will have on the total sensed gravitation) will be when δ = 0. Knowing the period, ω can be easily calculated. Equation 2 produces g_{TOT} = 5.207 x 10^{-3} m/s^2., directed toward the center of Phobos. This is the gravitational acceleration the astronaut will sense when working on the surface at the equator [30].

10.2 Surface Mobility: Proper Orientation

Astronauts of the Apollo program adapted to one-sixth gravity quickly, finding it easy to develop a method of loping across the surface of the Moon. For an astronaut on the surface of a very low-gravity body, like Phobos, translation will not be so simple. To calculate the optimal walking speed on the surface of a body, the Froude number (***Fr***) is utilized:

$$Fr = \frac{v^2}{gl} \quad (3)$$

where v is the speed of movement (in m/s), g is the total gravitation sensed at the surface (in m/s^2) and l is the leg length (in meters). For an average human male, l = 0.92 m. Additionally, ***Fr*** is about 0.25 for optimal walking speed, and about 0.5 for the walk-to-run transition speed [26].

Using these values, the optimal walking speed and walk-to-run transition speed for an astronaut on the surface of Phobos is 0.035 m/s and 0.049 m/s, respectively. When putting this into terms easier to visualize, these speeds are on the order of one-tenth of one mile per hour. At speeds greater than this, the astronaut will begin very long, parabolic trajectories that will be difficult to control. Therefore, if an operational concept dictated that it was necessary for an astronaut to walk on the surface of a very low-gravity body, a restraint system or attitude control system would be necessary to maintain a controllable upright posture.

In light of the difficulties associated with walking, an important question to ask is if walking is even the most desirable method of mobility? If the purpose of exploring the surface of Phobos is to perform field geology and collect surface samples, then the answer is likely no. The rationale for not employing significant resources to solve the challenges of walking in a very low-gravity environment was unwittingly given by Neil Armstrong during the Apollo 11 mission debrief [15]. When talking about surface operations and the optimal way to work, Armstrong said:

> *In general, there were a lot of times that I wanted to get down closer to the surface for one reason or another. I wanted to get my hands down to the surface to pick up something. This was one thing that restricted us more than we'd like…We should clear the suit so that you could go down to your knees, and we should work more on being able to do things on the surface with your hands. That will make our time a lot more productive, and we will be less concerned about little inadvertent things that happen.*

Therefore, to simplify surface exploration and to better meet the exploration objectives, the preferred body orientation would be horizontal, more or less parallel to the surface, and within arms' reach of the surface.

10.3 Spacesuit Properties and Assumptions

The prone position affords a lower center of gravity, greater stability and a much more efficient body orientation for geological sample collection. The primary mode of mobility will not be the legs, but the arms. In this orientation, an astronaut would be able to hop across the surface of a very low-gravity body with much greater ease than any attempt to walk would allow. To understand the effect that this mode of mobility will have on an astronaut, however, it is necessary to calculate the motion as the astronaut propels him or herself using just one's arms.

To determine the motion, this paper will employ an estimated model of the Extravehicular Mobility Unit (EMU) currently used for EVA aboard the ISS. Figure 5 provides a gross estimation of the EMU geometry relative to the center of gravity (CG) [36]. Note that h_{CG}

represents the height of the CG above the surface. To calculate the motion, it will be assumed that the astronaut can be represented as a rigid body. This is not an entirely accurate assumption, but simplifies the analysis of the motion.

Under even very low gravitation, the positioning of the astronaut above the surface, as shown in Figure 5, is obviously not a stable one. With gravity pulling down, it is easy to envision that an astronaut will always eventually settle into a position where he or she is laying face-down on the surface. This analysis, however, assumes that this prone position is in fact stable; the way in which the astronaut physically maintains this prone position above the surface will be discussed later.

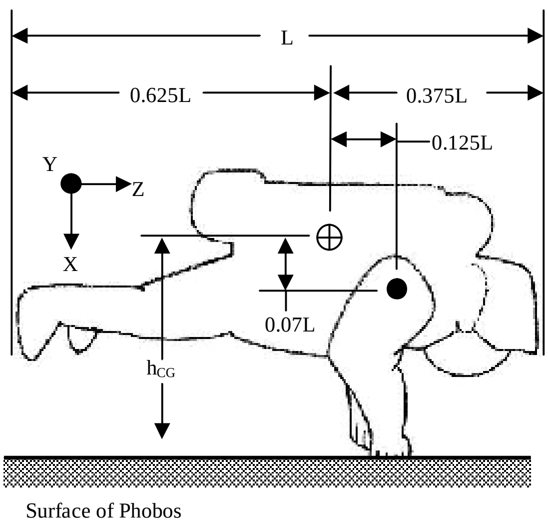

Figure 5. EMU estimated center of gravity geometry (The coordinate frame represents the EMU itself and not the local-vertical / local-horizontal coordinates at the surface of Phobos)

Table 6 provides the above measurements, along with a measurement for the estimated length of a fully-extended arm. Note that these estimated measurements are applicable only for the illustration that follows. A precise evaluation of the motion of the EMU (or any future spacesuit designed for exploration) would require precise measurements relative to the center of gravity, along with a precise measurement of the moment of inertia (I).

Segment	Representative Distance from CG	Distance to CG for L=2.0 meters
CG-Foot	0.625L	1.25 meters
CG-Shoulder (Horizontal)	0.125L	0.25 meters
CG-Shoulder (Vertical)	0.070L	0.14 meters
CG-Head	0.375L	0.75 meters
Shoulder-Palm	0.275L	0.55 meters
CG-Palm	0.345L	0.69 meters

Table 6. EMU estimated center of gravity geometry

For the purposes of this analysis, it will be assumed that the total mass (m) of the EMU-plus-crewmember is m = 300 kg, and the moment of inertia about the y-axis will be taken to be I_{yy} = 50 kg m^2, a number within the range of values measured on orbit as part of the testing of the Simplified Aid for EVA Rescue (SAFER) on STS-64 in September, 1994 [36].

Finally, to be able to examine the translational and rotational motion of the spacesuit on a very low-gravity body, it is necessary to know how much force an astronaut is capable of imparting. Per NASA's Man-Systems Integration Standards, the forces that a free-floating crewmember (one not held rigidly in place by a restraint) can impart are as follows in Table 7 [14].

Linear Force	Duration
4.4 N (1.0 lbf)	4.5 sec
22.2 N (5.0 lbf)	2.1 sec
44.5 N (10.0 lbf)	1.4 sec

Table 7. Maximum forces and duration capable of a free-floating crewmember [14]

10.4 Translational/Rotational Motion Analysis

The motion of the astronaut away from the surface must be calculated in two parts. First, while the crewmember is applying the force normal to the surface, the distances, velocities and accelerations due to the applied force can be calculated. Then, when the crewmember is in *free-flight* (meaning under only the net gravitational acceleration, g_{TOT}), those translational and rotational motions can be determined. Figure 6 shows the free-body diagram of the forces acting on the astronaut. While an astronaut would want to apply a force that creates not only upward motion, but forward motion as well, a force in only the $+h$ direction simplifies the calculations and is sufficient to illustrate the rotational motions. Note that the applied force generates a counter-clockwise (negative) rotation.

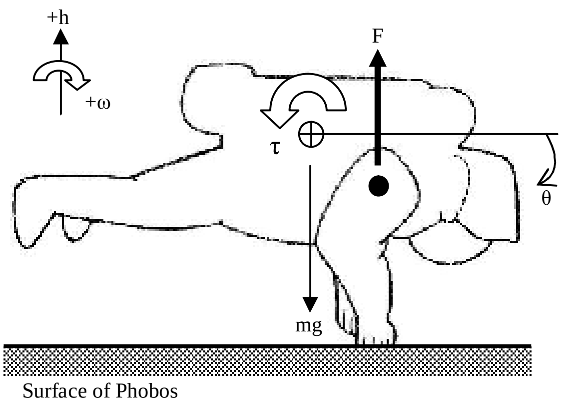

Figure 6. EMU free-body diagram

10.5 Motion During Normal Force Application

Using the mass value above, the translational motion experienced during the application of the forces in Table 7 (from this point forward termed the *push-off*) can be calculated using Equations 4-6.

$$a_t = \frac{F}{m} \tag{4}$$

$$h_{CG} = h_{CGo} + v_{h_o} t_{push} + \frac{1}{2} a_t t_{push}{}^2 \tag{5}$$

$$v_{h_{CG}} = v_{h_o} + a_t t_{push} \tag{6}$$

The term a_t in Equation 4 represents the translational acceleration normal to the surface, in m/s^2.

In Equation 5, the term h_{CG}, in meters, is the normal translational height above the surface of Phobos that a crewmember travels by extending his or her arms to their full length, just as one's hands are leaving the surface. As previously mentioned, the force is applied normal to the surface of Phobos, thus producing translational motion in the *+/-h* direction.

To calculate just the arm extension length, take the initial height of the CG, h_{CGo} = 0 meters. The term v_{h_o} is the initial vertical velocity, in this case v_{h_o} = 0 m/s, and t_{push} is the time over which the force is applied, in seconds.

In Equation 6, $v_{h_{CG}}$ is the positive vertical translational velocity at the end of the *push-off*, just as the crewmember's hands are leaving the surface. The initial vertical velocity, v_{h_o}, is zero. The motion for each applied force is listed in Table 8.

F (N)	t_{push} (s)	a_t (m/s^2)	h_{CG} (m)	$v_{h_{CG}}$ (m/s)
4.4	4.5	0.015	0.152+ h_{CGo}	0.068
22.2	2.1	0.074	0.163+ h_{CGo}	0.155
44.5	1.4	0.148	0.145+ h_{CGo}	0.207

Table 8. Translational motion and arm extension length

In a similar manner, the rotational motion due to the *push-off* can also be calculated, using Equations 7-9.

$$\tau = m a_t r = I a \tag{7}$$

$$\theta_{push} = \omega_o t_{push} + \frac{1}{2} \alpha t_{push}{}^2 \tag{8}$$

$$\omega_{push} = \omega_o + \alpha t_{push} \tag{9}$$

The term α in Equation 7 is the angular acceleration, in rad/ s^2, measured positive in the clockwise direction, and *r*, in meters, is the distance from the applied force to the center of gravity. Per Table 2, the horizontal distance from the CG to the rotation point of the shoulder is r = 0.25 meters. In Equation 8, θ_{push}, in radians, measured positive in the clockwise direction, is angle of rotation experienced by the astronaut while applying the force normal to the surface of Phobos, and θ_o is the initial rotational displacement. For a crewmember in the prone position, θ_o = 0 radians (i.e., the datum from which θ_o is measured is parallel to the surface). The term ω_{push} in Equation 9 is the angular velocity of the astronaut's rotation, in rad/s, measured positive in the clockwise direction. Again, since the astronaut starts this motion at rest, the value for the initial angular velocity, ω_o = 0 rad/s. The solutions for the rotational motion due to the *push-off* are listed in Table 9.

F (N)	t_{push} (s)	a_t (m/s^2)	α (rad/s$^{2)}$	θ_{push} (rad)	ω_{push} (rad/s)
4.4	4.5	0.015	-0.022	-0.223	-0.099
22.2	2.1	0.074	-0.111	-0.245	-0.233
44.5	1.4	0.148	-0.222	-0.218	-0.311

Table 9. Normal acceleration and arm extension length

The most notable result from Tables 8 and 9 are the similarities between the values of h_{CG} for the translational motion, and the values of θ_{push} for rotational motion. This shows that the varying forces applied by an astronaut result in very similar initial motion. Since this is the case, the remainder of this translational and rotational analysis will be completed using the values associated with an input force of F = 22.2 N.

10.6 Free-Flight Translational Motion

The rotational motion will have a considerable effect on the orientation of the astronaut, but the vertical translation of the CG is unaffected by rotation and can be calculated independently. With the linear velocity upward ($v_{h_{CG}}$) already known, the maximum translational height of the CG, and the time it takes to reach that point, can be calculated from Equations 10 and 11:

$$v_{h_{max}} = 0 = v_{h_{CG}} - g_{TOT}t_{ff} \qquad (10)$$

$$t_{ff} = \frac{v_{h_{CG}}}{g_{TOT}}$$

$$(h_{CG})_{Max} = h_{CGo} + v_{h_{CG}}t_{ff} - \tfrac{1}{2}g_{TOT}t_{ff}^{\,2} \qquad (11)$$

where t_{ff} , in seconds, is the *free-flight* time to the maximum height of the CG, $(h_{CG})_{Max,}$, measured in meters. To get the total time to $(h_{CG})_{Max}$, sum the values of t_{ff} and t_{push} . Table 10 presents the maximum vertical height and the duration for the positive vertical translational motion.

F (N)	t_{push} (s)	t_{ff} (s)	t_{CGmax} (s)	$(h_{CG})_{Max}$ (m)
4.4	4.5	12.68	17.18	0.92
22.2	2.1	29.84	31.94	2.83
44.5	1.4	39.88	41.28	4.64

Table 10. Time and distance to CG maximum height

As one would expect, a smaller force applied over a longer time period produces a smaller vertical hop, lasting less time. An increase in the gravitation sensed by the crewmember would decrease both the flight time and the height, as one would expect. Yet this only describes the positive vertical translational motion of the crewmember. The rotational motion becomes more complex.

10.7 Free-Flight Rotational Motion

As shown, a constant force applied normal to the surface generates positive vertical translational motion. However, since the force is not applied at the CG, it creates a counter-clockwise rotation about the CG as well. It stands to reason, then, that to avoid any rotation in this case, one may move the CG to be coincident with the shoulder. However, as an astronaut will want to move both upward and forward while exploring a very low-gravity body, there is no way to place the CG such that the horizontal and vertical components of such a force are directed through the CG. Therefore, in this orientation, any force applied by the astronaut will create a rotation.

To understand the motion as the astronaut moves upward and rotates counter-clockwise, however, the analysis must be able to determine when and if the feet strike the surface.

It turns out that, for any given applied force, this is dependent on h_{CGo}, the initial height of the CG above the surface, measured in meters. Due to the estimated geometry of the EMU, the minimum value of h_{CGo} cannot be less than 0.28 meters. At that initial height, the crewmember is lying in contact with the surface. Additionally, the maximum value of h_{CGo} cannot be greater than the arm extension length subtracted from the CG-to-palm length of 0.69 meters. Table 11 shows the minimum and maximum initial CG height for each input force.

F (N)	Arm ext. length (m)	$(h_{CGo})_{Min}$ (m)	$(h_{CGo})_{Max}$ (m)
4.4	0.152	0.28	0.538
22.2	0.163	0.28	0.527
44.5	0.145	0.28	0.545

Table 11. Minimum and maximum initial CG height

It is unrealistic to explore the surface of a very low-gravity body while actually lying on the surface, so for the first example, assume the crewmember is positioned just above the surface. Choose h_{CGo} = 0.35 meters; this means that in the prone position, the front of the EMU is just 7 centimeters from the surface. Knowing this value for h_{CGo}, one can determine if the feet come into contact with the surface, and if so, at what time (t) and at what angle (θ), using the geometry from Figure 7 and Equations 12-17 below:

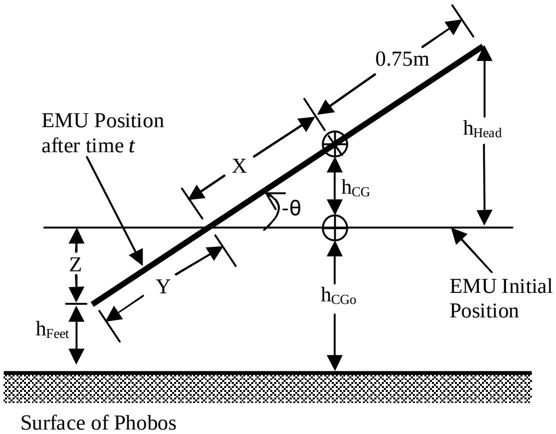

Figure 7. EMU geometric analysis

$$\theta = \omega_{push} t \quad (12)$$

$$X = \frac{h_{CG}}{\sin(\theta)} \quad (13)$$

$$Y = 1.25 - X \quad (14)$$

$$Z = Y \sin(\theta) \quad (15)$$

$$h_{Feet} = h_{CGo} - Z \quad (16)$$

$$h_{Head} = (X + 0.75)\sin(\theta) \quad (17)$$

where θ is in radians, and X, Y, Z, h_{Feet}, and h_{Head} are measured in meters. When the value for either h_{Feet} or h_{Head} is zero, that part of the EMU is in contact with the ground. It should be noted that the starting point of this *free-flight* rotational motion coincides with the end of the *push-off*, as this is the second part of the rotational motion analysis. Using the geometry above, and knowing the applied force (*F*), the duration of the applied force (t_{push}), and the initial height of the CG (h_{CGo}), it is possible to iterate upon the *free-flight* time (t_{ff}) to determine if and when the feet strike the surface during the positive vertical translation. Table 12 displays the results for h_{CGo} = 0.35 meters.

F (N)	Time (t) when h_{Feet},=0	h_{CG} (m)	θ (rad)
4.4	8.5 sec	0.723	-0.617
22.2	4.1 sec	0.809	-0.704
44.5	3.0 sec	0.821	-0.716

Table 12. EMU position when feet contact surface

Table 12 shows that increasing the force causes the feet to strike the surface sooner, but at a greater angle. This implies that, given a sufficient input force, a relationship exists that may cause the positive translation of the CG to outpace the rotation counter-clockwise, thus keeping the feet from ever touching the surface during the positive vertical translation. This gives rise to two other questions. First, rather than increase the input force further, does a value exist within the allowable range of h_{CGo} that causes the positive translation of the CG to outpace the rotation, allowing unimpeded rotation throughout the entire positive vertical translation? Second, what is the continuing motion of the EMU throughout a particular trajectory? These two topics will be addressed serially in the next two sections.

10.8 Rotational Motion: Altering h_{CGo}

By varying h_{CGo} and performing the same analysis as before, it is possible to determine whether or not a lower limit of h_{CGo} exists, within the allowable range for each applied force, that results in unimpeded rotation throughout the positive vertical translation. This *threshold* limit will be termed $(h_{CGo})_T$.

For an input force of 4.4 N, no allowable value of h_{CGo} produces unimpeded rotation; the astronaut's feet always contact the surface during the positive vertical translation. At $(h_{CGo'})_{Max}$, the feet contact the surface at t = 11.89 seconds, with a CG height of 1.020 meters, and a rotation of 0.954 radians counter-clockwise.

At this applied force, an astronaut would never propel him or herself into an unimpeded rotation, where one is unable to use one's legs to dampen rotational motion. What is unknown is how effectively an astronaut *can* use his or her legs to dampen out such a motion. Also note that these numbers apply only to the gravitation of Phobos. If an astronaut was exploring any other very low-gravity body, with its own unique gravitational field, this analysis would need to be repeated for said gravitation.

When the force applied is equal to 22.2 N, a value for $(h_{CGo})_T$ does exist where the astronaut's feet do not contact the surface during the positive vertical translation. Instead, the astronaut rotates, unimpeded, counter-clockwise for the entire trajectory, not making initial contact with the surface until he is descending toward it approximately 59 seconds later. Unimpeded rotational motion occurs for any value of h_{CGo} = 0.416 meters or greater, up to $(h_{CGo'})_{Max}$ Figure 8 depicts the astronaut's motion with h_{CGo} = $(h_{CGo})_T$ = 0.416 meters. The closest the astronaut's feet come to the surface is a single millimeter, when θ = -0.918 radians

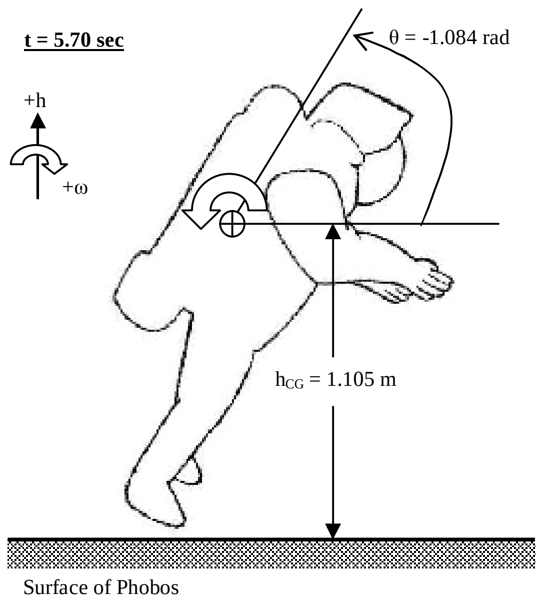

Figure 8. No contact motion, F=22.2N, h_{CGo}=0.416 m

A value for $(h_{CGo})_T$ also exists for F = 44.5 N. For this applied force, no contact will be made with the surface for any value of h_{CGo} = 0.403 meters or greater. In this case, at t = 4.1 seconds, the astronaut's feet are just two millimeters from the surface. This occurs when θ = -1.059 radians, and h_{CG} = 1.091 meters.

From this information, a relationship can be discerned between the applied force and the value of h_{CGo} for which the rotational motion is unimpeded throughout the positive vertical translation. To more accurately define this relationship, however, more data points for the maximum forces a free-floating astronaut can impart (along with the duration of that force application) would be needed.

Yet from even these few data points, the relationship shows that as the applied force is increased, the value of $(h_{CGo})_T$ .decreases. This would suggest that, to improve controllability of a spacesuit on the surface of a very low-gravity body, the center of gravity should be positioned as close to the front of the chest as possible, thus possibly allowing the crewmember to use his or her arms and legs to more effectively control the translational and rotational motions.

Knowing that it is possible to push vertically with enough force to cause unimpeded rotational motion, it is worth comparing the full motion of 1) the impeded rotational-motion, and 2) the unimpeded rotational-motion trajectories.

10.9 Translational/Rotational Motion: A Full Trajectory Analysis

The full trajectory motion for all three applied forces can be completed, but for illustration purposes, this paper will focus on the trajectory associated with F = 22.2 N. To show two cases, and the resulting motion on the astronaut, this section will begin with the impeded trajectory of h_{CGo} = 0.35 meters, and then examine that of h_{CGo} = $(h_{CGo})_T$ = 0.416 meters. In this way, one can see the effect that foot-contact with the surface has on the crewmember's trajectory.

Additionally, due to the fact that no collision is elastic, it is advisable to assume some level of rotational damping. Damping will be caused by such variables as the flexibility of the crewmember, the density and composition of the very low-gravity body's surface, and the pliability of the segments of the spacesuit that contact the surface. However, since it is dependent on so many variables, the first two trajectory analyses (as stated above) will arbitrarily assume that rotational damping will be 50 percent; in other words, each time the EMU contacts the surface, it loses 50 percent of its angular momentum.

Yet it is important to show that any arbitrarily chosen value for rotational damping has a considerable impact on the trajectory. The third trajectory analysis in this section will return to a value of h_{CGo} = 0.35 meters, but will consider any collision between the astronaut and the surface losing only 25% of it angular momentum. While this again simply chooses another arbitrary value for rotational damping, it best demonstrates the significant influence that varied levels of damping have on the rotational motion.

10.10 Trajectory Analysis: h_{CGo} = 0.35 meters

The parameters resulting from the first time the astronaut contacts the surface were calculated in Section 10.6 and reported in Table 12. The rotation is traveling counter-clockwise, but upon contact with the surface (at t = 4.1 seconds), it changes direction to clockwise, retaining one-half of its angular momentum. This, along with the rest of the flight trajectory, is shown graphically in Figure 9. Note that the horizontal arrangement does not indicate horizontal motion; the translational motion is confined to the +/- h direction (normal to the surface).

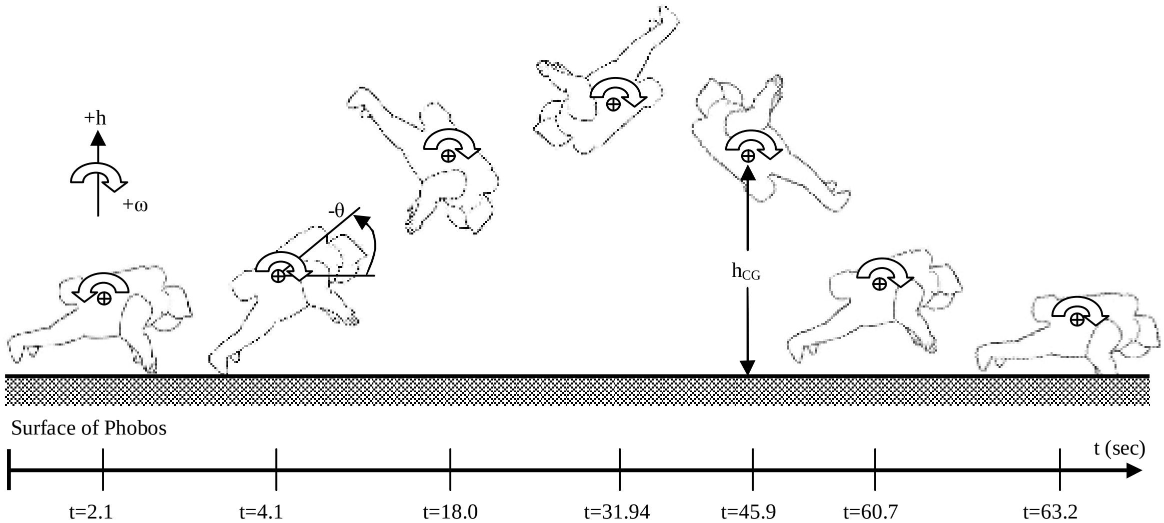

Figure 9. Illustration of the flight trajectory, F=22.2N, h_{CGo}=0.35 m

t (sec)	2.1	4.1	18.0	31.94	45.9	60.7	63.2
h_{CG} (m)	0.513	0.809	2.326	$(h_{CG})_{Max}$ = 2.832	2.329	0.679	0.289
$v_{h_{CG}}$ (m/s)	0.155	0.134	0.061	0.0	-0.084	-0.161	?
θ (rad)	-0.245	-0.703	0.924	2.549	4.107	5.901	6.192
ω (rad/s)	-0.233	0.117	0.117	0.117	0.117	0.117	?

Table 13. Flight trajectory parameters, F=22.2N, h_{CGo}=0.35 m

Table 13 presents the various parameters of motion for a number of points throughout the trajectory. At t = 2.1 seconds, the crewmember has just completed the ***push-off*** and enters the ***free-flight*** portion of the trajectory.

Figure 9 illustrates the considerable risk to the crewmember due to the rotation about the CG; at times, the astronaut cannot actually see the surface. Additionally, at t = 60.7 seconds, the CG is at a height of 0.679 meters – roughly the distance from the CG to the palm of a fully extended arm – and has rotated nearly 340 degrees. In this orientation, the astronaut's hands will be the first body part to touch the surface. Depending on the amount of energy the astronaut can absorb with his or her arms, it is likely that the collision with the surface will cause the astronaut to oscillate upward again, repeating this motion until all energy has been dissipated.

10.11 Trajectory Analysis: h_{CGo} = 0.416 meters

To understand how the value of h_{CGo} affects the trajectory's rotation, it is necessary to examine a case where $h_{CGo} \geq (h_{CGo})_T$.. Per Section 10.8, where $h_{CGo} = (h_{CGo})_T$ = 0.416 m, the astronaut's feet will come within one millimeter of the surface but will not make contact during the positive vertical translation. This will significantly alter the trajectory, as the rotation will continue in a counter-clockwise direction until the astronaut has come back down and some portion of the spacesuit makes initial contact with the surface. Figure 10 depicts this motion.

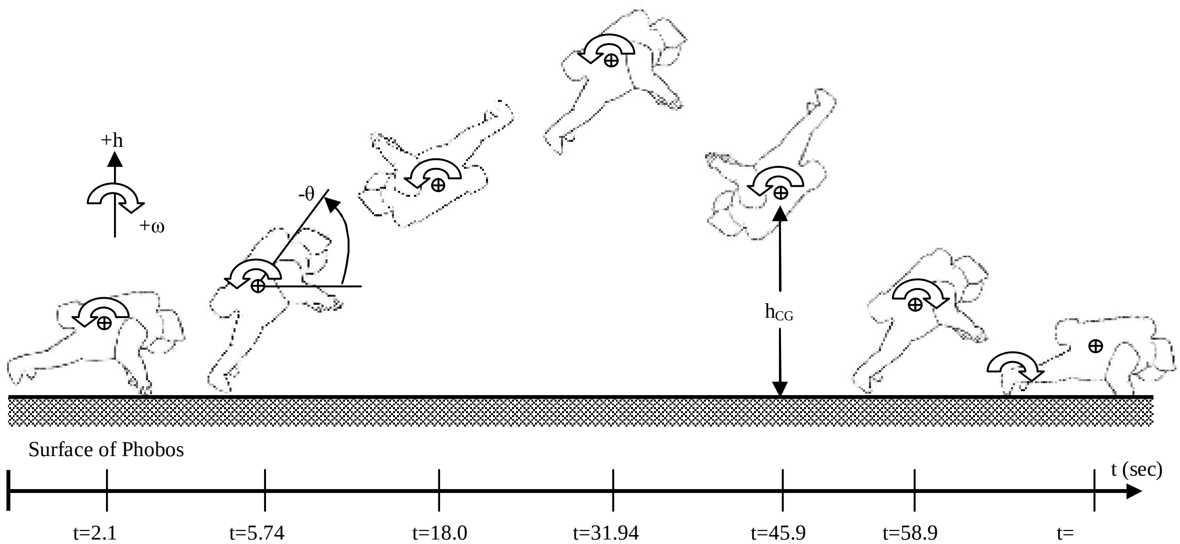

Figure 10. Illustration of the flight trajectory, F=22.2N, h_{CGo}=0.416 m

t (sec)	2.1	5.74	18.0	31.94	45.9	58.9	57.8
h_{CG} (m)	0.583	1.105	2.392	h_{CGmax}= 2.898	2.391	1.001	0.28
$v_{h_{CG}}$ (m/s)	0.155	0.125	0.061	0.0	-0.084	-0.152	?
θ (rad)	-0.245	-1.084	-3.951	-7.200	-10.454	-13.494	-12.791
ω (rad/s)	-0.233	-0.233	-0.233	-0.233	-0.233	0.117	?

Table 14. Flight trajectory parameters, F=22.2N, h_{CGo}=0.416 m

Due to the fact that this rotation is unimpeded, the astronaut continues to rotate counter-clockwise throughout the positive and negative vertical translations, until the feet contact the ground at t = 58.9 seconds. At this point, the astronaut has rotated through nearly 775 degrees of counter-clockwise rotation over almost one minute of free flight. In the descending phase of this trajectory, the initial contact with the surface results in continued clockwise rotation.

However, if the astronaut's feet do not skid across the surface, the rotation about the CG shifts to rotation about the feet, since the rate of negative vertical translational motion is greater than the rotation rate. The feet thus remain in contact with the surface, and the relative motion introduces some small amount of horizontal motion of the CG to the right. Again, depending on the astronaut's ability to damped that motion as the hands come into contact with the surface, the clockwise rotation may shift back about the CG, causing the astronaut's legs to cartwheel overhead.

Choosing any value of h_{CGo} greater than $(h_{CGo})_T$ has less effect on the trajectory. For a value of h_{CGo} = $(h_{CGo})_{Max}$ = 0.527 m, the astronaut's feet first contact the surface at t = 59.3 seconds (vice 58.9 s), θ = -13.578 rad, and h_{CG} = 1.061 m. The one time this may be a more significant issue is if initial contact with the surface occurs very near to θ = ±π/2 rad, where a slight difference in contact angle results in the difference between the crewmember ending up on his or her back rather than facing the surface. The higher starting point results in the astronaut striking the surface in a slightly more upright orientation, but results in a very similar clockwise rotation about the feet toward the surface.

10.12 Trajectory Analysis: Altered Damping

For the third and final trajectory analysis, the value of the initial CG height will return to h_{CGo} = 0.35 m, as it was in Section 10.10. However, the rotational damping will be reduced from an arbitrarily chosen value of 50% to another arbitrarily chosen value of 25%. The initial motion will be identical to that of Section 10.10. The difference will arise after time t = 4.1 seconds, when the counter-clockwise rotation alters to clockwise rotation resulting from the collision between the astronaut's feet and the surface. Rather than maintain one-half of its angular momentum, however, the altered value for rotational damping allows the rotation to maintain three-quarters of its momentum, significantly changing the astronaut's trajectory. Figure 11 below depicts the altered damping trajectory.

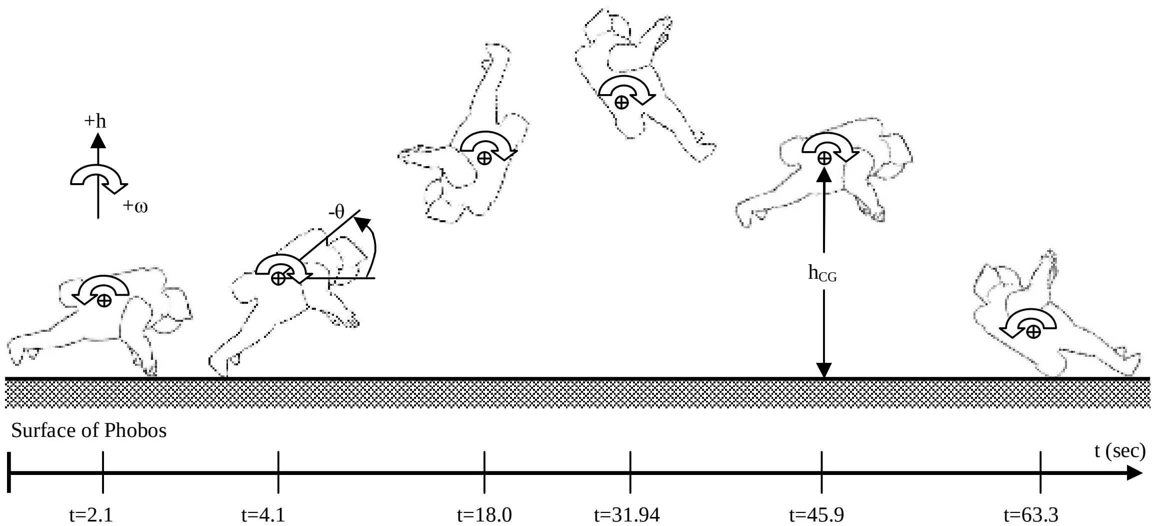

Figure 11. Illustration of the flight trajectory, F=22.2N, h_{CGo}=0.35 m, 25% rotational damping

t (sec)	2.1	4.1	18.0	31.94	45.9	63.3
h_{CG} (m)	0.513	0.809	2.326	$(h_{CG})_{Max}$ = 2.832	2.329	0.279
$v_{h_{CG}}$ (m/s)	0.155	0.134	0.061	0.0	-0.084	?
θ (rad)	-0.245	-0.703	1.736	4.173	6.605	9.649
ω (rad/s)	-0.233	0.175	0.175	0.175	0.117	?

Table 15. Flight trajectory parameters, F=22.2N, h_{CGo}=0.35 m, 25% rotational damping

With less rotational damping, the astronaut now rotates through over 550 degrees in the clockwise direction, nearly 200 degrees more rotation than with the rotational damping at 50%. In this third case, when the astronaut makes contact with the surface during the negative vertical translation, the astronaut is on his or her back, and when the astronaut's heels strike the surface, it initiates another counter-clockwise rotation, placing the astronaut farther onto his or her back. With no way to damp the vertical motion, one would expect the astronaut to strike the surface and oscillate upward.

Additionally, there is no way to predict whether the astronaut's heels will skid across the surface, and thus without knowing the variables that effect damping, it is pointless to speculate on the values of $v_{h_{CG}}$ and ω after the heels have made contact. From the illustration, the only necessary information can be easily deduced; an astronaut landing on his or her back in an environment with rough-hewn features faces a great safety risk.

10.13 Trajectory Analysis: Conclusions

More than either of the other illustrations, this third case shows the dangers of not maintaining attitude control. Altering the input force, its duration, or its angle relative to the surface changes the trajectory. Recall, as well, that Phobos was modeled as a sphere with constant bulk density, but that will not be the reality for any low-gravity body. Odd shapes, voids throughout the substructure, and varying bulk densities due to composition will create inconsistent gravitational fields. Additionally, changing latitude away from the equator reduces centripetal acceleration, thus increasing the gravitation sensed by the astronaut.

Move away from Phobos, to a smaller body, and the motion becomes more problematic. All other parameters equal, if a potential target had a mean radius just one-quarter of that of Phobos (i.e., r = 2.275 km; still large by NEO standards), the total gravitation sensed by the astronaut would reduce to $g_{TOT} = 6.16 \times 10^{-4}$ m/s^2. Using the calculation method previously described, and taking F = 22.2 N, $(h_{CG})_{Max}$ would change from a height of about 2.8 meters to more than 20 meters high, taking over 250 seconds to reach that height. This means that an astronaut applying that moderate force would be in *free-flight* for over eight minutes.

To further demonstrate the vast differences caused from the numerous variable parameters, double the period of rotation of this new body. The altered period of rotation changes the centripetal acceleration at the surface. The period of rotation now becomes 15.31 hours, the value for the sensed gravitation increases to $g_{TOT} = 1.163 \times 10^{-3}$ m/s^2, $(h_{CG})_{Max}$ = 10.89 meters, and the time to the maximum height is 135 seconds.

While this is not much of an improvement for the astronaut's working conditions, it does demonstrate the effect that so many variable parameters have on surface mobility. The challenge, then, for a very low-gravity exploration architecture, is to develop hardware and operational concepts that allow widely varying potential targets to remain within the program's capabilities.

11. ISS Utilization for Surface Mobility Research

Hardware and operational-concept development for a low-gravity exploration program would be well served to employ a progressive approach, utilizing all available resources to test out the devices and techniques that will be needed to both keep astronauts safe and allow them to be productive. Sometimes those two objectives – safety and productivity – run counter to each other. In an effort to make astronauts safer, for example, alterations to a spacesuit design may reduce dexterity, visibility, even operability, leading to not only a less efficient working environment, but sometimes even inducing additional risk. Due to the nature of the exploration destinations, and even with robotic precursor missions paving the way to a particular target, unknowns are inevitable. The only way to overcome those *unknown* unknowns is by developing and vetting an array of both hardware and concepts, thus providing the astronauts on location the opportunity to choose the tools and techniques best suited to the local environment and the exploration objectives.

NASA has a number of assets for development and testing, including the Neutral Buoyancy Laboratory and the Virtual-Reality Laboratory, both of which are housed at NASA's Johnson Space Center. Each facility, however, will have benefits and deficiencies with respect to very low-gravity exploration development. The zero-gravity aircraft that NASA utilizes to test and validate concepts and hardware, for example, are capable of flying parabolic flight paths that can imitate roughly any gravitational force, from microgravity to lunar gravitation and beyond. The parabolas, however, only yield continuous test-time on the order of 30 seconds. Additionally, since the inside of an aircraft is a confined environment, it is not an ideal setting to test large scale, long-duration motion response hardware.

NASA understood these limitations when it addressed the design and validation of the SAFER. Built as a self-rescue device for an astronaut that becomes inadvertently separated from the spacecraft during an EVA, SAFER uses cold-gas nitrogen thrusters to provide attitude control and propulsion. Instead of attempting to validate its design in a simulated environment, NASA chose to test it in low-Earth orbit as part of a Designated Test Objective (DTO). Flying on STS-64 in 1994, STS-88 in 1998 and STS-92 in 2000 [8], the SAFER was used during an EVA on each flight, to improve the design and validate it as a redundant safety system. In a similar manner, very low-gravity EVA hardware and operational concepts can and should be tested through a series of EVAs conducted onboard the International Space Station.

11.1 Questions Requiring Resolution

The theoretical analysis of motion presented in this paper is just that – theoretical. As such, a number of assumptions were necessarily made to complete the analysis. However, it is important to determine actual motions, to identify the perceived hardware and operational-concept needs from actual needs. Time and again, the men and women of NASA's astronaut corps have demonstrated an acute adaptability to working in the EVA environment; some of the perceived challenges regarding very low-gravity EVA may be less significant if astronauts can minimize the severity of those challenges simply through adaptation.

A series of tests performed through the use of ISS-based EVAs could provide information regarding the capabilities of the human-in-the-loop, along with valuable feedback that focuses development of hardware and concepts to meet the actual low-gravity EVA needs, rather than theoretically-perceived needs. The testing should be progressive, as well, and the program be given sufficient time to use the information learned from each test to develop and design the objectives and hardware for subsequent testing. In this way, the ISS becomes a test-bed for very low-gravity EVA research.

First, however, some of the basic questions need to be answered, to help define such a low-Earth orbit research program. This paper has focused primarily on surface mobility, because it is the quintessential core competency for very low-gravity body exploration. If an astronaut cannot safely and efficiently move about on the surface of a very low-gravity body, a program built on the exploration of such bodies is futile. Geological exploration is most important when the samples are collected within the geological context of the body. This means that, ideally, samples are taken from various, distinct locations about the body. Therefore an operational concept that restricts astronauts to one small area – working from a platform attached to a spacecraft that has *landed* on the surface, for example – is less than ideal. Every effort should be made to provide the astronauts the greatest degree of freedom possible. The answer to each question will likely raise more questions, but by giving this program sufficient time to mature, the evolution will be natural, and the likelihood of success for the first very low-gravity EVA will increase exponentially.

The following are but some of the questions regarding surface mobility that may be answered through an ISS-based EVA research program. The list is in no way comprehensive, but it does attempt to capture the concerns addressed in the previous pages of this paper regarding the risks to the astronaut as he or she attempts to navigate one's way over the surface of a very low-gravity body.

1) What is the minimum level of gravitation that an astronaut can safely and effectively operate in without any sort of restraint system (no tethers, no handholds, no anchors of any kind)?

2) How well and how quickly can an astronaut adapt to using only the minimum amount of force needed to maneuver about on a low-gravity body?

3) How well and how quickly can an astronaut learn to direct the applied forces to limit vertical linear motion without the aid of an attitude control system (i.e., moving horizontally over the surface rather than up and down)?

4) Using one's hands to propel the spacesuit across the surface places the gloves at risk of a cut or tear that could lead to the termination of an EVA. What design alterations would negate this risk without significantly degrading the dexterity needed to meet exploration objectives (e.g., removable gauntlets, reinforced glove substructure, etc.)?

5) How well can an astronaut absorb and dissipate the energy encountered during the negative vertical translational motion, to avoid bouncing off the surface?

6) What is the optimal way to design a spacesuit and the ancillary hardware that allows an astronaut to remain in the prone position without the majority of spacesuit touching the surface (e.g., bi-pods on the feet, braces extending from the spacesuit chest, etc.)?

7) How does a damper system integrate with the rest of the spacesuit? While an astronaut may be able to control negative vertical translational motion with one's arms, is it wise to have pressurized gloves in contact with the surface as the entire weight of the spacesuit is descending toward the surface?

8) How effectively can an astronaut use one's legs to create a rotational moment that opposes the rotational moment caused by the arms during *push-off*?

9) Can a redesign of the spacesuit boots assist further in controlling rotation and protect the pressurized volume from cuts and tears (e.g., flexible tips that act as springs, etc.)?

10) If an astronaut can use one's legs to help control rotation, is there an optimal θ_o (angle of the suit relative to the surface; for the previous analyses, θ_o = 0 radians) that best allows the astronaut to control rotation?

11) An attitude control system of some kind will be necessary for any operational concept that gives the astronaut six-degree freedom of movement. What are the minimum required capabilities of such a system (e.g., does it control only rotation, does it only control pitch and roll but not yaw, does it use cold gas jets which may plume dust-covered surfaces, etc.)?

12) In the prone position, the visor may come within very close proximity of the surface. What helmet/visor design alterations are necessary to improve safety and at the same time limit the loss of visibility?

13) In the prone position, it will be difficult for the astronaut to see forward or to the sides. What sort of onboard visualization system will aid in mobility, spatial awareness and photo documentation (e.g., camera views integrated into a heads-up display visible on the inside of the visor, a helmet with 360 degrees of visibility, etc.)?

These are the types of questions that will need to be addressed before a spacesuit that is optimally designed for very low-gravity exploration can be built. From the previous analyses, the motion of an astronaut on the surface of Phobos has the potential to be hazardous. Only by examining the capabilities of the human in the loop with respect to force inputs, and the level of ability to control the motion, can spacesuit design parameters be defined. Without first obtaining this experimental and empirical data, the spacesuit design will force the operational concepts to find ways to work around the deficiencies of the spacesuit.

The following is one very simplistic way to at least begin to determine the answers to some of the questions above. It may not be the ideal experimental setup, but it is presented here to show one way of using ISS as an EVA research facility.

11.2 A Simplistic EVA Evaluation Aboard ISS

The zenith side of the U.S. Destiny Laboratory (Lab) may be a feasible location to perform a series of Designated Test Objectives. The Lab itself is about 8.5 meters long, with a diameter of about 4.4 meters [8]. Figure 12 shows the Lab as it was being installed during STS-98, in 2001 [21]. Figure 13 shows a fly-around photo taken during STS-127, in 2009 [18]. In the region on the Lab noted as the *primary area of interest* in Figure 11, two rows of handrails run aft from the forward end-cone.

Figure 12. ISS Destiny Laboratory during install, STS-98[21]

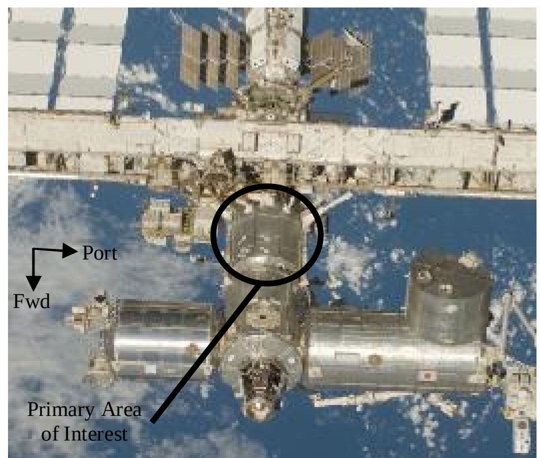

Figure 13. ISS Destiny Laboratory, STS-127 fly-around[18]

Knowing the basic dimensions of the module, it can be estimated from Figures 12 and 13 that the handrail rows are about 1.3 meters apart. Additionally, the distance from the forward end-cone to the point where the S0 truss segment attaches to the Lab is about 4.85 meters. In this region between the handrail rows, an astronaut could use a system of slide wires and cables to evaluate many of the topics discussed in Section 11.1.

To begin, an astronaut would install a slide wire stanchion onto the end of each handrail row, running forward and aft. This would allow two separate, parallel slide wires to run from the forward end cone to a handrail stanchion near the location where the S0 truss segment attaches to the Lab, an overall length of approximately 4.85 meters. Then, an astronaut would employ a modified work station that attaches to the front of the EMU. This work station has two armatures, each with a reel housing at the end of it. The reel housings are in line with the CG with respect to the z-axis of the EMU. Within each reel housing is an inelastic cable connected to a constant-force spring. The astronaut positions him or herself between the slide wires, and attaches each inelastic cable to the respective slide wire by a small hook at the end of the inelastic cable. Figure 14 shows the astronaut between the slide wires, with the inelastic cables attached. The astronaut's hands are resting on the top of the Lab as he waits for the system to equilibrate.

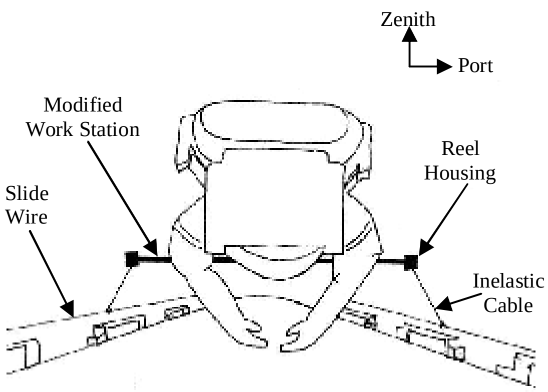

Figure 14. Astronaut positioned on Lab zenith

By knowing the relative geometry, it is possible to equip each reel with the appropriate constant-force spring to mimic any desired gravitation. The geometric dimensions in Figure 15 are rough estimations made only for illustration purposes. As is evident, if any such DTO were to be performed on the ISS, a great deal more thought and consideration would go into every aspect of the experiment. This simple example, for instance, does not account for the variations in slide wire tension, and assumes cables and slide wires that are perfectly inelastic.

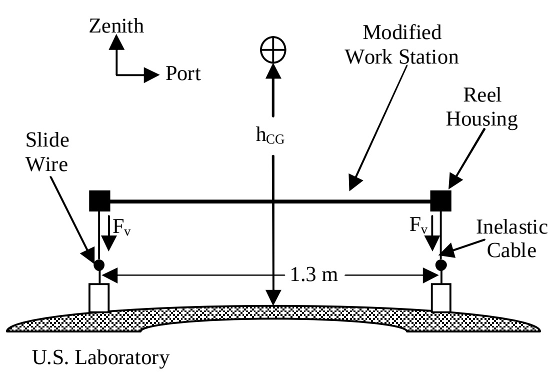

Figure 15. Experiment geometry
(Astronaut not shown for clarity)

The required value of F_v is one-half the force of gravity on, for this example, Phobos.

$$F_v = \frac{1}{2} m g_{TOT} = 0.781\ N \tag{18}$$

This is the amount of force required of each constant-force spring to mimic the gravitation that an astronaut would experience on Phobos. As the astronaut pushes off from the Lab, the reel housings are mounted on swivels, so that his or her rotation is not impeded by the cabling holding the modified work station to the slide wire. By employing the slide wire, an astronaut can translate both vertically and horizontally over the entire slide wire length. In this way, an astronaut can evaluate and offer feedback regarding many of the questions listed above. To further improve results, instrumentation to measure linear and rotational rates, and the input forces that generate those rates would be needed.

Figure 16 shows an astronaut after he has pushed off from the Lab. It is quickly apparent that even an evaluation like this has limitations. As the astronaut rotates, the location of the reel housings mounted to the modified work station moves farther out of alignment with the CG. Designing a modified work station that places the heel housings as close to the CG as possible along the z-axis will help alleviate this problem. Yet even in the simple configuration presented in Figure 16, an astronaut will be able to provide valuable commentary regarding his or her ability to use one's legs to dampen rotational motion, the ability to limit input forces, and whether the astronaut can direct those forces at will.

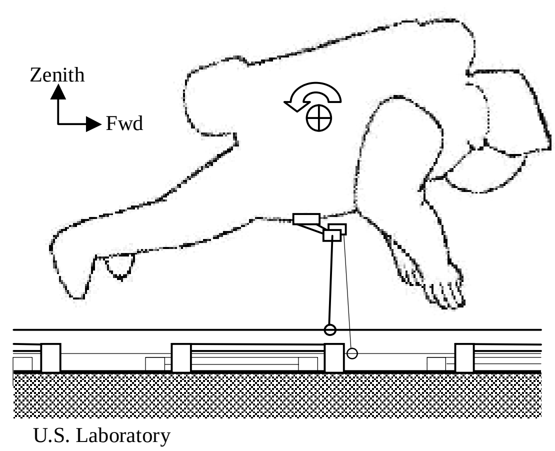

Figure 16. Free-floating astronaut under simulated Phobos gravitation

Additionally, altering the force of the constant-force spring system will provide astronauts an opportunity to weigh in, through crew consensus, on what is the minimum acceptable gravitational force that would not require a restraint system. This alone will be a significantly valuable piece of information, as it may rule out a large number of potential targets.

The feedback provided by the astronauts will help bound some of the challenges. Understanding the adaptability of an astronaut in such an environment – even when simulated – and quantifying the level of control said astronaut can attain will have significant impacts on system requirements. By understanding the level of control, designers do not need to assumptions when designing accompanying hardware such as motion damping systems and attitude control systems. The greater the astronaut's capabilities to maintain body control, and the greater the understanding of those abilities, the more precisely designed those accompanying automated systems can be. And any time a system can be designed to actual needs, rather than assumptions, results in a more efficient system.

As testing progresses, this apparatus can be used to test various damping systems, attitude control systems, and eventually spacesuits designed for very low-gravity EVA. It is also very likely that creative engineers and scientists can devise other ways to configure worksites aboard ISS to cater to this type of testing. It should be noted that EVA time is valuable aboard ISS, and these evaluations, at least in the beginning, are likely to be added to an EVA timeline that is primarily focused on repairing ISS hardware. As such, it is imperative that the configuration, setup and execution of these Designated Test Objectives is simple and can be accomplished as quickly as possible. An idyllic configuration would be one that utilizes an area of ISS seldom traveled, where the experimental apparatus can remain deployed between EVAs. This gives the astronauts the opportunity to meet more research objectives as time allows during EVAs primarily focused on other, unrelated tasks. In this way, ISS can be that unparalleled research facility that paves the way for the future exploration of the solar system.

12. Spacesuit Orientation Methodology

As was mentioned earlier, there is still the open question of how to secure the spacesuit in a stable prone position, thus permitting the above described operational concept for surface mobility. The surface of a NEO presents a plethora of dangers to a spacewalking astronaut, not the least of which is sharp, jagged rocks. Contact with the surface must therefore be minimized. This paper will present one possible way to overcome this significant issue.

Figures 17 and 18 represent two views of the same crewmember. In these figures, the spacesuit is equipped with a system the author has termed the *Cricket System*. Four legs extend from the primary life support system (i.e., the backpack), designed to a prescribed length based on both the results of ISS evaluations regarding adaptability, and crewmember stature. These legs act, in essence, like the legs of a table, supporting the spacesuit in an orientation that optimizes both surface translation and geological exploration. Even at very low-gravity, the crewmember will descend to the surface over time. The *Cricket System* eliminates that falling motion, stabilizing the spacesuit in a relaxed orientation, allowing the astronaut to focus less on body control and more on geological exploration.

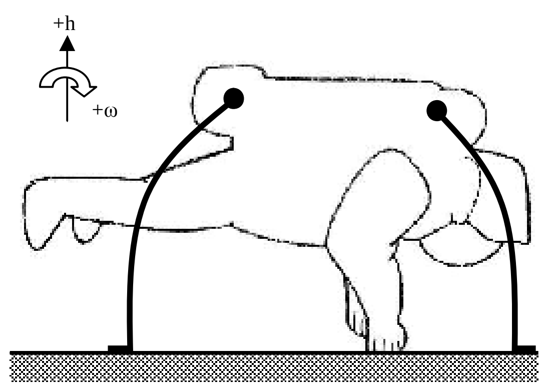

Figure 17. Cricket System: side view

The *Cricket System* also possesses a number of other desirable attributes. The biggest danger of this system is that a crewmember propels himself or herself across the surface of a very low-gravity body, and in the process, rotates to a point where he or she ends up on one's back, like a tortoise. The feet of this system, however, could be geometrically designed to increase stability and impart a righting moment, should the crewmember land askew.

The legs of the *Cricket System* also become an excellent platform, if designed for operability, for the tools necessary for geological exploration. Deployed sample collection bags would ease that process for an astronaut, as would tool stowage, thus keeping the most essential tools within easy reach of a prospecting crewmember.

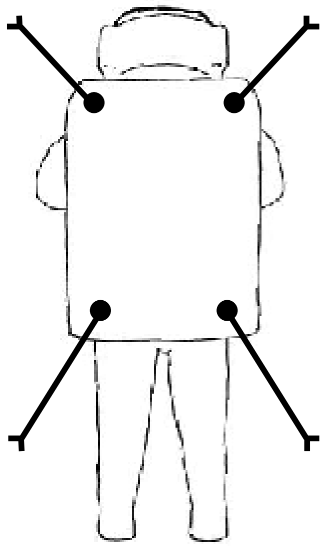

Figure 17. Cricket System: top view
(crewmember facing down toward the surface)

As a passive system, it has desirable attributes. However, if testing showed that a crewmember would need assistance in damping vertical motion, the *Cricket System* possesses the potential to support such a system. By incorporating a damping system into the feet, the *Cricket System* could absorb much of the negative vertical motion of a translating crewmember, thus reducing the amount of force the crewmember would need to absorb with his or her hands. In this way, the crewmember would, in theory, only be touching the surface to collect geological samples, and to begin a translation.

Regarding rotations during translation, designers may be able to incorporate the damping system into an overall, active attitude control system, using some of the stored energy from each "landing" to impart a force opposite the sensed rotation caused by a crewmember's arms at the beginning of the next translation. In this way, the spacesuit itself may require little or no other attitude control.

Another option for rotational control, in conjunction with the *Cricket System*, would be to find a way to incorporate the capabilities of the astronaut in further influencing rotational motion. Figure 18 depicts a crewmember wearing a modified boot. The tip of the boot would be flexible, much like the fins worn by a scuba diver.

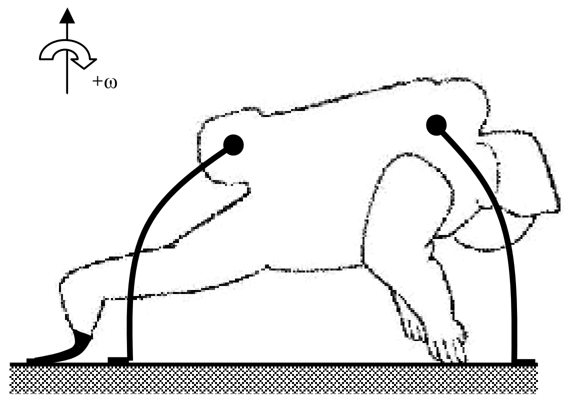

Figure 18. Cricket System: boot tip modification

The concept would be to utilize the spring force of the boot tips, to counteract the rotational motion induced by a crewmember pushing off the surface of a very low-gravity body with his or her hands. The astronaut would employ his or her legs to generate a small force that would, in theory, create and equal and opposite torque upon the spacesuit; the negative torque generated by the arms during push off would be nullified by the positive torque generated by the legs. In this way, a crewmember would need no active attitude control system; he or she would simply bound, face down, across the surface of a NEO.

This is obviously a design that would need to be tested in either a simulated zero-g environment – such as aboard a zero-g aircraft – or tested as part of a DTO aboard the ISS. The necessity for a DTO would be not only to determine the optimal flexibility of the boot tips, but to determine the adaptability of the astronauts to utilize this system in a controlled manner.

One immediate and obvious challenge to the *Cricket System*, however, would be its method of deployment, and the associated complexity. In the configuration shown in the figures, a crewmember could not fit through a nominally designed airlock hatch. Thus the *Cricket System* would need to have the ability to move from a *stowed* position to a *deployed* position, thus allowing an astronaut to move through the airlock hatch without worrying about damaging hatch seals. It may be as simple as designing each leg to rotate about its connection point, to streamline the system with the crewmember, or it may be as complicated as some sort of telescopic system. This is obviously open work, and a large number of questions would need to be answered to decide on the best methodology, but nonetheless it is not insurmountable by any means.

There is certainly a vast amount of open work to solve the issues associated with surface mobility. How it should be done, and even whether it actually can be done, loom large for any exploration architecture that counts very low-gravity bodies as possible destinations. By synergizing the creative engineering talents in the aerospace industry with the operational experience gained through Apollo, the space shuttle and the ISS programs, however, there is no doubt that methods can be devised that will at least allow humanity to attempt the exploration of NEOs and other small celestial bodies. The question then becomes “what sorts of activities are the explorers of these bodies going to conduct?” The starting point for that answer again comes back to the Apollo program.

13. Apollo Scientific Experimentation Setup

The first EVA of every Apollo lunar surface mission had the highest priority tasks assigned to it, in case the crew was forced from the surface before the nominal end of the mission. Some of these tasks – such as Lunar Flag Placement and TV camera setup – were not scientific in nature, but human in nature. Others, however, were purely scientific. One such activity was the *Contingency Sample Collection.*

Beginning right away with Apollo 11, and conducted on every mission through Apollo 15, the crew, upon reaching the surface, would collect surface rock and soil samples. Only a few minutes would be spent on this task, but the notion was that, should the crew need to abort the EVA and leave the surface of the Moon, there would be some geological samples aboard the LM for return to Earth. Apollo 16 and 17 did not perform this task; the author conjectures that the engineering team was confident that the crew would not be forced to leave the surface on such short notice, and thus chose to use the valuable EVA time for other tasks.

One of these other such tasks that was conducted on every Apollo mission, was the setup of the surface experimentation package. Apollo 11 deployed the Early Apollo Scientific Experiments Package (EASEP), consisting of a laser ranging retroflector, passive seismic experiment and a lunar dust detector. The experiments were easy to deploy but the crew found it difficult to find a level spot near the LM for deployment. Apollo 12 through 17 each deployed an Apollo Lunar Surface Experimentation Package (ALSEP). The exact experiments that comprised the package evolved from flight to flight; some experiments were often repeated, while others were unique to a specific mission. Apollo 12 had six experiments, including a solar wind spectrometer and a lunar surface magnetometer. Apollo 15 had eight experiments, including the solar wind spectrometer, as well as a cold cathode gauge and a superthermal ion detector. Apollo 17 also had only six experiments, but its package consisted of such experiments as a lunar surface gravimeter and a lunar ejecta and meteorites experiment.

Difficulties in deploying the ALSEP were often encountered, and the crew was forced to spend valuable EVA time troubleshooting the contingencies. Apollo 14 had similar difficulties to Apollo 11 regarding finding a level spot for deployment, while on Apollo 15, the crew had difficulty drilling holes into the lunar surface for a heat flow experiment.

For NEO exploration, the number of experiments that will require deployment by spacewalking astronauts is dependent on the capabilities of the robotic precursor missions. Should a robotic mission be capable of performing spectroscopy, or measuring gravitational fields, experiments of this nature may be redundant, making space available for unique research on another aspect of the NEO. For example, Abell et. al. suggests that the “active detonation of a kinetic energy experiment after deployment of a seismic network would…serve to measure the interior of the NEO while gaining insights into the effects of crater excavation” [2]. The deployment of such a network, for example, may require the real-time assessment that can only come from the feedback the geological team on Earth gets from the astronauts in situ.

In this way, it is difficult to predict the types of experiments that the science teams will want to conduct, but it is easy to imagine that some portion of the EVA time that the astronauts spend on the surface of a NEO will be dedicated to the deployment of scientific experiments. Due to the challenges associated with working in an environment much less stable than the surface of the Moon, however, experiment designers should pay particular attention to ensuring simple deployment, to minimize both crew time that would be lost to troubleshooting a contingency, and the possibility that the contingency cannot be overcome and the deployment of the experiment is aborted.

14. Field Geology

The mantra of EVA aboard the ISS is that *slow is fast*. In the micro-gravity environment of low-Earth orbit, a spacewalking crewmember finds it easy to start his or her motion, and difficult to stop that motion. Utilizing handrails to traverse about the exterior of the ISS, crewmembers rely on upper body strength and leverage to arrest their motion. Stopping when both hands are very close together is much harder than when the hands are separated. Stopping becomes even easier when the hands are also out of plane, providing leverage. And as is obvious, any input rate to begin a motion must be nullified to stop a motion. Therefore, the mantra that *slow is fast*.

By beginning every motion slowly, the rate is low. A slow rate of motion is easier to stop, requiring less muscle input. This may seems insignificant at first glance, as the environment is weightless and an astronaut must simply maintain control of the overall mass of him or herself plus the spacesuit. However, over six hours, fatigue plays a major role in the level of success attained by the spacewalk. Tired hands struggle to actuate tools, and fatigue in general often leads to a loss of focus. A six and a half hour EVA that has been conducted flawlessly for first 95% of the spacewalk can turn in an instant, when fatigue results in carelessness and a critical piece of hardware is accidentally set adrift. Not only is the item lost overboard, but it becomes a recontact danger for the ISS itself, sometimes requiring the station to perform a costly (and unplanned) avoidance maneuver. These induced risks to crew and vehicle are minimized through extensive training, and by instilling the belief in all spacewalking crewmembers that conserving energy is essential to success, and that the most effective way to conserve energy is by remembering that *slow is fast*.

This same philosophy will be invaluable on the surface of a very low-gravity body. Whether moving across the surface or seeking the perfect position to photograph a geological find, moving slowly conserves energy and allows an astronaut to maintain a higher level of body control. For an astronaut exploring the surface of a NEO, however, this mantra will likely be most significant with respect to field geology. Every movement across the surface will be, in essence, to reposition oneself to continue the geological survey and sample collection. This paper will attempt to identify the major types of scientific activities conducted on the lunar surface by the Apollo astronauts, which represent an excellent starting point for NEO surface-exploration operational concepts. However, whether a crewmember is collecting surface samples, attempting to dig a small trench, or taking core samples, the success of field geology will depend entirely on a crewmember's ability to maintain good body control. Moving slowly will allow an astronaut to work efficiently and effectively, thus likely resulting in a high quantity of quality field research.

14.1 Surface Sample Collection

This field geology activity was the simplest for the Apollo astronauts, and will be the simplest for the astronauts exploring the surface of a NEO. Every Apollo mission performed this task, which can be broken into two categories: rock samples and soil samples.

Using the training received in geology prior to flight, the Apollo astronauts attempted to collect unique rock samples from the various locations visited. Using such tools as the tongs, the rake and the scoop, as well as their hands, rocks were collected from nearly every location visited; and when time permitted, the crews often worked diligently to document the sample collection from each site through words and photography, to help maintain the geological context. To understand the quantity of samples collected, consider EVA2 from Apollo 15. During a geological traverse, the crew stopped at five separate stations. At the third station alone, the crew collected 93 samples, including the famous *Genesis Rock*.

Similarly, the crews used sample collection bags to stow soil samples, most often scraped up from the surface using the scoop. The length of the tools, in conjunction with the limited flexibility of the Apollo spacesuit, sometimes produced inefficient results. At times the crews struggled pouring contents into sample return bags, leading to more exertion (and frustration) than necessary. On Apollo 16, the crew reported that the straps holding the sample bags to the spacesuit PLSS would not stay tight, and considerable time throughout the day was spent cinching these straps back in place. Additionally, this same crew reported during

EVA3 that the sample bags were top-heavy and when they were loaded, had a tendency to tip over, thus spilling some of the sample back to the surface.

Many of these challenges were the direct result of the inflexibility of the spacesuit, and therefore the need to use digging-type and grabbing-type tools. This further signifies the importance of developing some method of positioning the crewmembers nearer to the surface, where they can use their hands in concert with short-handled (and thus dexterous) tools. By designing tool stowage and sample collection stowage into the legs of the *Cricket System*, for example, an astronaut would be able to expend his or her energy on the most important tasks at hand, namely the efficient collection and documentation of surface samples, rather than searching for operational work-arounds to hardware limitations.

14.2 Trench Sample Collection

To better understand the lunar composition, scientists determined the need to take soil samples from areas below the surface of the Moon. Beginning on EVA2 of Apollo 12, astronauts began taking soil samples from the bottom of shallow trenches, which they dug using the long-handled scoop. The method for sample collection mirrored that for the surface soil samples, except for the fact that the astronaut first had to dig a shallow trench, and then take the soil sample from the bottom of that trench.

During that first attempt to dig a trench, on Apollo 12, the crew reported that they were able to dig down 20 centimeters, and that depth was only limited by the tool's handle length; had they longer tools, the crew reported that they could have dug deeper. Conversely, during Apollo 15, Irwin reported that he had only been able to dig a trench to a depth of about one foot; after that point, he stated that it felt as though he was scraping bedrock.

For a NEO astronaut, this task would not be so simple. If the surface density was low, and the astronaut moved slowly, it may be possible to dig a trench, thus allowing soil samples to be taken below the surface. However, without some sort of restraint system in place, any force the astronaut imparts while pushing a trenching tool against the surface will likely cause him or her to move. As an astronaut traverses about on a NEO, this could result in inconsistent sample collection, as varying surface compositions may make trenching impossible for an unrestrained crewmember.

During the development phase, testing could be conducted to bound the abilities of an astronaut to trench the soil as a function of the effective gravitational force. Such testing would provide hardware designers with the necessary feedback to determine optimal tool configurations, as well as whether trenching needs to be an action decoupled from the astronaut.

If an astronaut in a very low-gravity environment cannot dig down into the soil without pushing himself or herself away from the worksite, it may be necessary to develop tools that can be placed on the surface and dig a trench autonomously. This introduces another level of complexity into the hardware design, however. With all the various types of NEOs – some with a rocky composition, some merely rubble piles [11], some comprised primarily of metals – how would such an autonomous tool attach itself to the surface in a manner sufficient to react the loads encountered while trenching the soil.

This question is much larger than just trenching tools, however. Taking core samples, for instance, and drilling – discussed in the following sections – likely need to be decoupled from the astronaut, and thus also need attachment methods to the various types of NEOs. Even more significantly, though, is whether an attachment system can be devised that allows the visiting vehicle to maintain contact with the surface, rather than flying in some station-keeping position. This is a question that will likely generate a considerable amount of research in the coming years.

14.3 Core Sample Collection

Of the often-performed geological tasks from the Apollo program, this is likely the most difficult to transpose directly to a NEO. Every Apollo mission extracted core samples, starting with Apollo 11. And to the credit of the hardware designers, only Apollo 11 had significant issues with core sample collection.

The Apollo method for core sample collection was simple: place a core sample tube upside down on the surface – so the tube's opening was pressed into the soil – and drive the tube into the surface using a hammer. For Apollo 11, the issue was simply the design of the core sample tubes. The tubes were designed with a bevel to compact the soil and keep it inside the tube. The lunar soil just below the surface was already quite compact, and when Aldrin repeatedly struck the 35 centimeter long tube with the hammer, he reported that it would go no further than eight or nine inches down. Striking with increasing force, Aldrin actually bent one of the extension handles before aborting the task with a less-than-optimal sample. For Apollo 12, the tubes were redesigned, and no further issues were encountered for the remainder of the program.

This highlights the challenge of core sample collection on a very low-gravity body, however. To illustrate, examine an astronaut attempting to drive a core sample tube with a hammer on the surface of Phobos. Recall that, for Phobos, g_{TOT} = 5.207 x 10^{-3} m/s^2, and the assumed mass of an astronaut in a spacesuit was 300 kg. This means that the astronaut is held to the surface by a force of just 1.56 Newtons. If a hammer with a mass of 3 kg could was accelerated from rest to a velocity of 10 m/s in one second, it would strike a core sample tube with 30 Newtons of force.

While the tube will dissipate some of that energy by sinking into the soil, the astronaut will need to dissipate the remainder. It is not difficult to envision that, by striking a core sample tube, an astronaut will propel himself or herself into the air, in a manner similar to that which was analyzed in the *Surface Mobility* section. Therefore, it is likely that if core samples are desired, hardware whose operation can be decoupled from the astronaut will be necessary.

Again, due to the multitude of NEO compositions, and the specific nature of each individual celestial body, the development of a suite of tools to address this single problem will be required. This paper will present one theoretical piece of hardware that, under specific conditions, may suffice.

Figure 19 represents a tool designed to drive a core sample tube into the surface of a NEO. Its method of attachment to the surface is through a chemical bond, so it would not be as effective if used in a dusty environment, where it cannot chemically adhere to the surface and provide a reactionary force to the piston housed in the upper chamber. The core sample tube would be installed and held in place by a set of guide arms, which would ensure proper alignment. The astronaut would then press the tool to the surface, where the pads would adhere. When ready, the astronaut could them press a button and the tool would begin driving the core sample tube into the soil using the piston, which could be powered by small, replaceable, high-pressure gas cartridges. Upon the successful insertion of the core sample tube, the astronaut would pull the bottom tab from each pad, leaving a layer of the chemical adhesive behind; the newly exposed layer of pad would now be ready for use.

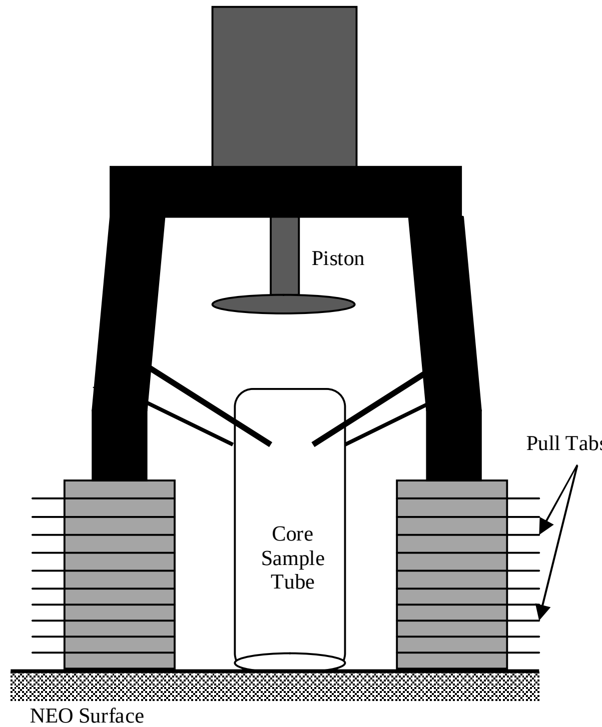

Figure 19. Theoretical example of a core sampling tool

This tool, however, would not necessarily need to be used just with core sample tubes. If a restraint system on the surface of a NEO was desirable, this tool could be designed to also drive pitons into the surface; the astronaut could then route a tether through the piton, providing some physical restraint.

As previously stated, Figure 19 is simply a theoretical example of a tool that may aid an astronaut in a number of different ways. As has been learned through years of exceedingly complex orbital EVAs, however, any tool or hardware design meant to aid or simplify a task for a spacewalking crewmember must remain true to that purpose; tools and hardware that are inherently complex often lack robustness, resulting in crew time spent troubleshooting a problem rather than accomplishing primary objectives, but beyond that, complex hardware often lack operability, leading to fatigue and frustration over the tool's use. In an environment as challenging as a NEO, tools and hardware need to be designed, first and foremost, for ease of operability.

14.4 Deep Core Sample Collection

Beginning with Apollo 15, the last three Apollo missions brought with them a tool called the Apollo Lunar Surface Drill (ALSD). The drill was designed for two separate tasks. First, it was designed to drill holes into the surface for the Heat Flow Experiment. Additionally, it was to take a deep core sample by driving the long, segmented tube into the surface to a depth of 2.5 meters. The crew of Apollo 15 experienced the difficulty in designing hardware for an environment where prototype testing is not feasible.

During EVA1, Scott reported encountering some difficulty with the drill at a depth of just 30 centimeters while drilling the first of three holes for the Heat Flow Experiment. Spending on the order of 20 minutes troubleshooting this problem, he was only able to get the drill to drive to a reported depth of 170 centimeters. He then proceeded to drill the second hole and encountered the same problem. Due to his high O2 usage, Mission Control called him off drilling the third hole, leaving that task for EVA2.

Upon returning to drilling tasks on EVA2, Scott attempted to drill a core sample. A better flute design allowed the sample tube to auger to the full depth, but the hole became compacted and Scott could not remove the core sample stem. Again, high O2 usage forced him to abandon the task to the next EVA. As a result of the drilling problems, EVA2 fell about one hour, forty minutes behind the nominal timeline.

During EVA3, Scott was assisted by Irwin in attempting to remove the drill from the compacted hole. After 10 minutes of very hard work, they were able to extract it; in the process, Scott sprained his shoulder. Scott reported that drilling was the hardest EVA task he performed.

A new, improved drill design was flown on Apollo 16, which allowed Charlie Duke to drill his first Heat Flow Experiment hole the full depth of 2.5 meters in just one minute. Additionally, a jack-and-treadle system was developed to aid in lifting the drill from each hole.

Two items are immediately apparent when considering the challenges encountered by Apollo 15. First, any long-duration mission like that to a NEO should carry with it enough experiments to allow the crew to abort an individual experiment if it is obvious that the hardware design will significantly impact the nominal EVA timeline. The number of days available for proximity operations will vary depending on the orbital dynamics of the target, and as such, any time wasted troubleshooting design flaws is just that, wasted.

Second, in a very low-gravity environment, an astronaut will not be able to manipulate a drill without a restraint system. If the spacecraft is able to “land” and remain on the surface, an astronaut may be able to operate a drill from a foot restraint attached to the spacecraft, but barring something this stable, it is not a task worth considering.

There have been a number of papers written that propose ways of mining asteroids [9,29]. If the need for deep core samples is great, much research will need to be done to determine the best ways to operate drills on the surface of a NEO independently from the astronauts. Even the setup of something so massive will be a daunting task for an unrestrained crewmember, and thus it will be imperative to find ways to conduct this sort of research with little to no aid from the astronauts.

15. Geological Traverse

The first three missions to the surface of the Moon relied on the astronauts on locomotion to explore the region around the landing zone. Apollo 11 remained within close proximity to the LM for the duration of their single EVA. On Apollo 12, the crew hiked approximately 4,300 feet during their second EVA to retrieve parts of the robotic *Surveyor III* spacecraft, and on Apollo 14’s second EVA, the crew covered about three km on a roundtrip excursion to Cone Crater.

Exploring by foot became a thing of the past starting with Apollos 15. For that mission and the subsequent missions, the astronauts were able to explore the surface using the Lunar Rover Vehicle (LRV). Apollo 15 used it for all three EVAs, traveling as far as six km from the LM during EVA3. Apollo 16 traveled as much as 11.4 km from the LM during their final EVA, and Apollo 17 covered a roundtrip distance of 20.4 km during their second EVA.

For astronauts exploring a NEO, the opportunity to traverse great distances using a vehicle such as the LRV is not feasible, due to the very low-gravity. One could envision intrepid engineers devising ways of using propulsive units, or designing vehicles to operate effectively in such a low-gravity environment, but the complexity added by such simple tasks as egressing and ingressing the vehicle every time an astronaut wants to collect a sample may well render this concept superfluous.

Additionally, although NEOs do have a considerable size range, it is likely more practical to spend an EVA in a specific area of the NEO, and then have the spacecraft place the astronauts on the following EVA in a different area of interest. The advantage of this approach, especially when one considers that the vast majority of NEOs will be rotating, is that the crew aboard the spacecraft can, through observations and discussions with the scientific teams on the ground, pick and choose the most ideal location for each and every EVA.

However, the use of the LRV during the Apollo program brings forth a question regarding the maximum distance the astronauts should be from the spacecraft; should an emergency arise, the crew would need to be able to respond to the emergency within a specific period of time to minimize the risks to the spacewalking crewmembers.

For the Constellation program, the ESAS report was very clear on the limiting distance [33].

If the tasks are located farther than the emergency return walking distance (approximately 30 minutes), way stations to provide suit consumable resupply should be provided.

Thus, the astronauts should be no more than 30 minutes from the airlock, traveling at a nominal speed on foot. This 30-minute constraint is a wise one, especially in a NEO environment, where the surface composition may well put the crewmembers at a heightened risk to a spacesuit emergency.

Yet how does one quantify the translation rates of the spacewalking astronauts when every target will have a different gravitational force? For the Moon, the experience of Apollo gave a good indication for the speed with which an astronaut could move without exerting excessive energy. For NEO missions, it will be very difficult to judge translation rates, especially during the first few EVAs, and that lack of knowledge will likely require that the astronauts not venture as far as may be desirable.

16. Photographic Documentation

Photography has always been a part of the space program. The images of boot prints imprinted in the dust of the lunar surface, of astronauts saluting the flag, of the entire sphere of the Earth within the boundaries of a single frame are iconic. Photography (for this paper, photography really represents both still images and video) has been the most effective public-relations tool, connecting the vast majority back on Earth to the few adventurers soaring the heavens.

Photography is more than just inspirational images, however. The astronauts of the Apollo program used photographic documentation to survey the various sites where samples were to be collected, to provide the geological teams back on the ground with context. By examining not only the rocks themselves, when they were brought back home, but also the context in which they were discovered and collected, the scientific teams could better interpret the history of the Moon.

Aboard the ISS, the use of photography plays a critical role in construction. After completing a specific task – the change-out of an orbital replacement unit, for example – the astronauts are often directed to provide close-out imagery of the worksite. This imagery provides the ground teams with a complete understanding of the configuration of thermal blankets and access panels, allowing more accurate thermal analyses.

And photography has become instrumental in the space shuttle program since the Columbia accident. Recall that Columbia broke apart during entry in February, 2003, due to a hole in the leading edge of the left wing, caused during ascent two weeks earlier by a piece of foam from the External Tank. That damage went undetected, and as Columbia passed through entry-interface, plasma flowed into the cavity, ultimately leading to catastrophic failure and the loss of the vehicle and crew.

To ensure such damage did not go undetected again, NASA developed a procedure during space shuttle rendezvous called the Rendezvous Pitch Maneuver (RPM). Positioned directly under the ISS (and thus directly under the windows in the US Laboratory Module and the Russian Service Module, the space shuttle would perform a 360 degree backflip, while astronauts aboard the ISS would use digital still cameras outfitted with 400mm and 800mm lenses to take images of space shuttle. Those photographs would be downlinked to an inspection team on the ground, and that team would analyze every image, searching for any damage or misconfiguration. If an anomaly was discovered, the appropriate action would be taken to resolve the issue – STS-114 had to remove a gap filler from the belly of the orbiter during one EVA, and on STS-117, the crew had to repair an OMS pod blanket using pins and a surgical stapler [8].

These are but a few examples of the effectiveness of photography to accomplish not only public relations, but also critical science and critical engineering tasks. For the astronauts of a NEO mission, photography will also play a critical role. The biggest difference between prior missions and NEO missions will be the astronauts' capabilities to take high quality images.

The lack of restraints on the surface of a NEO will make photography a greater challenge. Therefore, it will be essential to develop new hardware, and new interfaces, to reduce the workload placed on the astronauts for imagery. One example that would be effective with the *Cricket System* would be to integrate still image and video capabilities into the spacesuit itself. Cameras mounted on the spacesuit could be controlled from an electronic pad worn on the wrist, which would allow the astronaut to toggle between cameras, zoom, pan and tilt. If the cameras were integrated into a heads-up display projected onto the visor of the helmet, an astronaut could view his or her surroundings through the various cameras, select the desired angle, frame the image and take exceptional pictures with little movement. This would reduce the physical exertion required of an astronaut, conserving energy, but it would also allow an astronaut to stay in a stable position while documenting the region in which he or she is working.

This is just one possible solution to the issue of properly outfitting the NEO astronauts with the capabilities to perform high-quality photographic documentation. What should not be overlooked is the amount of energy expended to conduct any operation during an EVA. Pressurized gloves lead to hand and forearm fatigue, and the impetus to complete all assigned tasks often leads to something akin to tunnel vision, where one loses track of time easily by focusing on all the work that needs to be completed.

The amount of energy required to retrieve a camera, find a stable body position that allows an image to be framed properly, take a requisite number of photos, stow the camera and return to the task at hand should not be overlooked. If the required energy is too great, there is a high likelihood that, as the EVA progresses and the astronaut tire, these sorts of tasks will be dismissed out of hand as not worth the effort.

This is not unique to photography, however. This is a lesson that has been learned through hundreds of spacewalks, and it proves the point time and again that operational considerations must be incorporated from the very beginning into EVA hardware design; the success of astronauts working on a NEO, the moons of Mars or any other very low-gravity body will require innovations in hardware and operational concepts. By incorporating the EVA lessons learned from the past 45 years, hardware designers can create tools and spacesuits that function in harmony with the spacewalking astronauts; if they are not, much of the astronauts' preflight training, and much of their energy during the spacewalks, will be spent finding ways to work around the limitations of the hardware.

17. Conclusions

The challenges over the next two decades for human space exploration may revolve around our ability, or lack thereof, to work in environments that take the most difficult aspects of lunar exploration and combine them with those difficult aspects of microgravity EVAs in low-Earth orbit. It will not be an easy task. This paper has addressed just a small portion of the challenges, by identifying some of the main points of an exploration architecture, including crew complement, surface mobility and field geology. There is a seemingly endless amount of open work.

The Apollo program, however, represents an exceptional starting point, from which scientists can develop experiments and mission designers can develop operational concepts that allow the goals of the science community to be met by the men and women traversing these challenging environments.

Additionally, as the author hopes he showed in this paper, the experience gained through the space shuttle and ISS programs cannot be overlooked. These programs provide invaluable information in identifying the most effective ways in which astronauts work in the EVA environment; designing hardware and operational concepts that take advantage of the efficient modes of operation will provide the greatest chance of success.

It is likely that many of these issues may not be resolved by the time astronauts head off to visit the first near-Earth object, but these issues, along with a host of ***unknown*** unknowns that will present themselves along the way, will require resolution before we can begin to extend the human presence farther out into the solar system.

Even in light of the broad challenges facing it, a very low-gravity body exploration program will provide great scientific benefit – many of these low-gravity bodies are relics from the formation of the solar system. Beyond that obvious reason, however, two other reasons exist for encouraging low-gravity exploration.

First, these potential targets may provide an opportunity to develop in-situ resource utilization techniques, allowing humans to more easily explore farther out into the solar system. If near-Earth objects, the moons of Mars, and even main-belt asteroids could serve as refueling depots, it would radically change the way vehicles and mission profiles are designed.

Second, as mentioned earlier, a portion of near-Earth objects cross Earth's orbit. The ones with a better probability of striking the Earth are termed Potentially-Hazardous Objects (PHO) [35]. Developing the ability to explore very low-gravity bodies leads to the ability to neutralize the threat a PHO may present to the Earth. In this way, a robust space exploration program built around low-gravity body exploration subsequently yields a robust planetary defense program.

Mars is a lofty and worthwhile goal when it is regarded within the context of solar system exploration. To have ready access to potentially hundreds of thousands of destinations, each unique, each challenging, each valuable, however, should be an ambition to great to pass over.

Authors' Note

This paper references a significant amount of data from the Apollo program. As such, it is impossible to annotate every such reference. The authors would like to be sure it is clear that all information in this paper from the Apollo program came from two references.

One source was the *Apollo Lunar Surface Journal*. It is edited by Mr. Eric M. Jones and Mr. Ken Glover. The *Journal* is an incredible, living document that is dedicated to accurately capturing the vast amounts of data from the Apollo program. It is available at www.hq.nasa.gov/alsj/frame.html. Note that this source is in the reference list, but the only place in the paper that it is referenced is the direct quote from Mr. Armstrong during the EVA technical debrief regarding surface operations [15].

The second source, which provided concise overview information for every Apollo EVA comes from the Lunar and Planetary Institute. This source is also listed in the references [23], but again due to the vast amount of information used from this website throughout the paper, no other specific references are made.

The authors would like to thank the editors and curators of these websites. Making the technical information from the Apollo program available to the public ensures that the lessons learned from an historic program will not be lost to posterity.

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