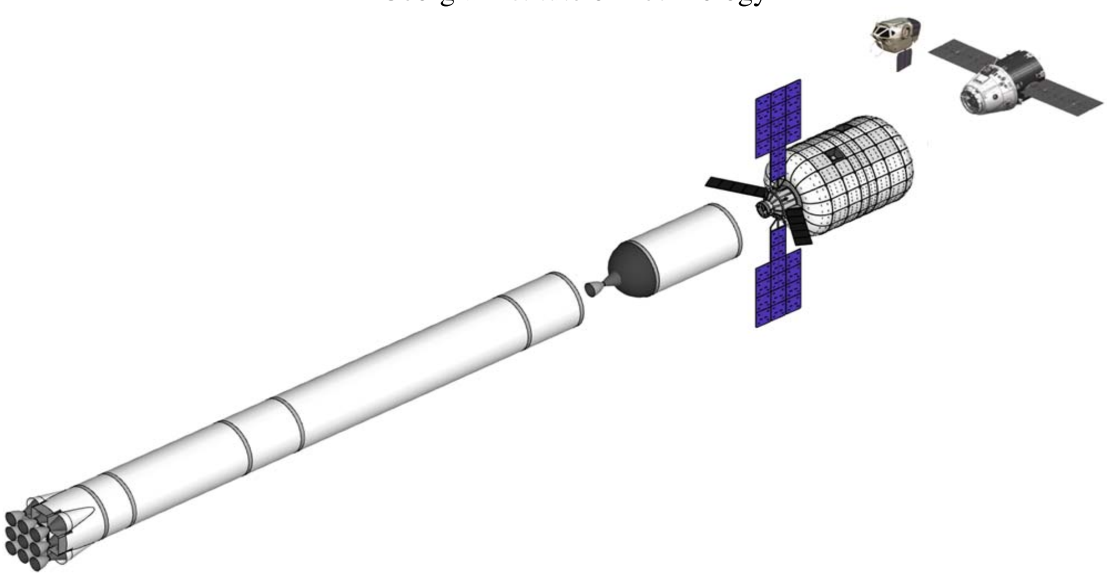
GEORGIA INSTITUTE OF TECHNOLOGY

CCS-ISP: Commercial Core Stages for In-Space Propulsion

A revolutionary, reliable, and responsible NEO crewed mission architecture

Patrick Chai, Sean Currey, Christopher Jones, August Noevere, and Grant Rossman
Georgia Institute of Technology



Dr. Alan Wilhite
Faculty Advisor

CCS-ISP: Commercial Core Stages for In Space Propulsion

Patrick R. Chai, Sean R. Currey, Christopher A. Jones, August T. Noevere

Graduate Research Assistants, Georgia Institute of Technology / National Institute of Aerospace, Hampton, VA 23666

Grant A. Rossman

Graduate Research Assistants, Space Systems Design Laboratory, Georgia Institute of Technology, Atlanta, GA 30332

Dr. Alan W. Wilhite

Georgia Tech Langley Professor, Georgia Institute of Technology / National Institute of Aerospace, Hampton, VA 23666

A crewed mission to a near earth asteroid would yield both scientific and engineering advancements. Visiting one or several of these objects would not only validate technologies that could later be used to visit the Moon or Mars, but would also develop our scientific understanding of asteroids and the solar system. NASA's Human Exploration Framework Team designed a baseline architecture and mission schedule that utilizes the Space Launch System heavy lift vehicle to send a three person crew to an asteroid. The architecture requires three heavy lift vehicles to launch all mission components. However, the enormous expense of this architecture limits NASA's ability to develop the crewed elements before 2025, making this architecture unaffordable and unsustainable. This study proposes an architecture that represents a paradigm shift in the way space exploration is conducted. By including commercial enterprises in this mission and encouraging competition, NASA can realize huge cost savings and schedule improvements over the baseline architecture. This architecture uses a commercial ascent vehicle core stage, which can reach orbit if a rocket is launched with no payload, as the in space propulsion system for both outbound and inbound burns. This stage can launch significant payload to the target destination. Refueling the core stage with commercial launch systems separates the propellant from the mission-critical elements, and using multiple commercial partners shortens the mission life cycle time and increases mission reliability. This architecture is more affordable and will be ready sooner than the current planned exploration architecture. Removing expensive and unnecessary systems and supplementing NASA hardware with existing commercial systems not only brings the program under the human space exploration budget but also opens up significant resources for developing the required technologies. Furthermore, this architecture is also extensible to other destinations of interest for human exploration.

1. INTRODUCTION

The solar system holds many secrets, and its ancient asteroids may shed light on some of them. A crewed mission to a Near Earth Object (NEO) would yield both scientific and engineering advancements.[1] The most prominent questions such a mission could answer include:

- What are the compositions of asteroids?
- Can asteroids be easily traversed or excavated?
- Are there resources on asteroids that can be used for human exploration or of other value?
- Can they be defended against if they are on a collision course with Earth?

Very little is known about the composition of asteroids or the value of the materials within them, and a very small percentage of the total number of NEOs has been discovered. A better understanding of the composition of asteroids will aid in the development of technologies for deflecting or destroying those that are potentially hazardous.

In addition to its scientific value, visiting one or several of these objects would also validate technologies that could later be used to visit the Moon or Mars.[2] Most NEOs require mission times between six months and two years. They are also in orbit around the sun; no human exploration mission has ever left cis-lunar space. This mission would represent a huge leap forward in crewed mission capabilities. In general, NEOs are difficult to reach. There have been a small handful of missions to NEOs,[3,4,5] and only one of which was a rendezvous rather than a simple flyby.

A crewed mission to a NEO will require significant technology development and mass in orbit. The United States and NASA must be willing to embrace shifts in how they approach mission design in order to accomplish such a goal within the budgetary and scheduling constraints that exist. The capabilities required to

Table 1: Asteroid Target Search Criteria

Criteria	Value	Justification
Total ΔV	< 7.5 km/s	Keep the total energy required below Mars mission requirement
Orbit Condition Code	< 3	Lower values indicate the orbit is better known. Mission success is highly dependent on precise trajectory placement
Absolute Visual Magnitude	< 2	Asteroids in this range are considered potentially hazardous were they to impact with Earth
Total Mission Duration	< 400 Days	This keeps the mission to within twice as long as a Lunar Mission but much shorter than a Mars mission
Potentially Dangerous	Yes	Asteroids that have a significant probability of impacting Earth are inherently more interesting
Launch Opportunities	2025-2035	Multiple opportunities afford the mission flexibility and the opportunity to send a robotic precursor
Rotational Velocity	< 1m/s	A large rotation speed increases the mission complexity and required propellant budget

Table 2: Potential Asteroid Target Information

Object Designation	Diameter (m)	OCC	Min ΔV (km/s)	Rotation Period (h)	Mission Duration	Asteroid Stay	Launch Opportunities
99942 (2004 MN4)	325	0	6.23	30.4	346 d	32 d	Twice from 2025-2030
207945 (1991 JW)	253-1131	0	7.49	unknown	370 d	32 d	Twice from 2025-2030

send humans to a NEO are within reach, but it will take a partnership of government and commercial entities to bring it to fruition. This study considers one possible approach that will permit affordable exploration of NEOs and beyond.

2. DESTINATION & RATIONALE

When selecting a target for the first NEO mission, the goal was to balance scientific value, technology development, and feasibility. Scientific value is characterized by size and composition, technology development by travel distance, and feasibility by shortness of mission times and knowledge of the target orbit. The Jet Propulsion Laboratory's NEO Human Space Flight Accessible Targets Study Database was used to locate NEO candidates for a 2025-2035 crewed mission.[6,7] The search constraints used are shown in Table 1. Of the many objects in the database, only two targets were found that match all of the search constraints: 99942 Apophis (2004 MN4) and 207945 (1991 JW). Table 2 summarizes the size of both targets and the performance requirements for each target.

99942 Apophis (2004 MN4) captured the public's attention in 2004 when astronomers noted it had a nontrivial chance of colliding with the Earth in 2029. Although updated trajectory simulation has ruled out the possibility of impact with the Earth in 2029, it will still pass below Earth's geosynchronous orbit and has a chance of colliding with the Earth again in 2036. A collision with Apophis would likely cause extensive local or regional damage. Due to the concern of impact, Apophis' orbital characteristics are known with relatively high accuracy. It is also one of two asteroids currently being considered by ESA to be visited by the Don Quixote[8] asteroid impactor mission to be launched this decade. This impactor mission will provide substantial robotic precursor data to aid in the detail design of a manned mission to the asteroid's surface.

207945 (1991 JW) is a large asteroid with a semimajor axis within 0.05 AU of Earth. Although not currently on the potential impactor list, it crosses Earth's orbit often and recently passed within 32 lunar radii of the Earth in 2010.

Either target is accessible and can provide useful information about the composition of NEOs and give insight into how to mitigate the threat of a NEO collision with Earth. Although both asteroids are good candidates for a manned mission, a mission to 99942 Apophis was selected for further analysis due to a lower propulsion performance (ΔV) requirement and the potential for a "free" precursor robotic probe mission.

Apophis is a relatively large asteroid, so an extended mission to this body would allow astronauts to explore a different region of the body each day. The asteroid's infamy as a potential threat would also capture the public's interest for a mission to this desination. Because the asteroid has already been extensively tracked, the certainty of its position and size measurement is higher than most other bodies. Lastly, its slow rotation allows for relatively easy docking with the asteroid, while at the same time offering some free thermal management from sun exposure.

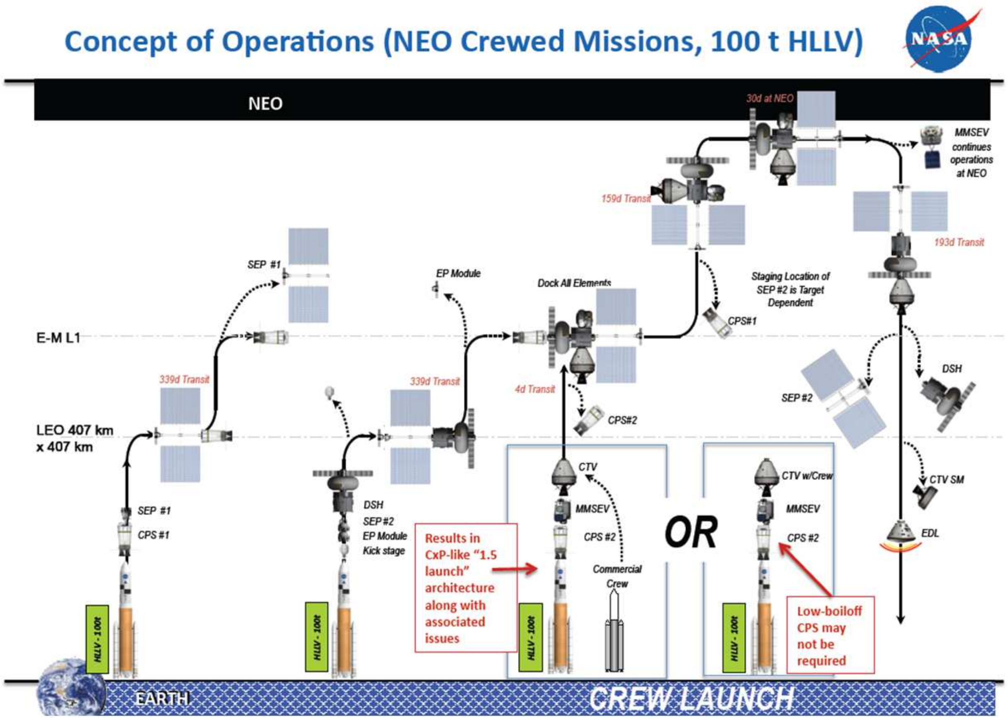


Figure 1: NASA Human Exploration Framework Team Concept of Operation for a Crewed Mission to a Near Earth Object, Reproduced from Ref. 9

3. REFERENCE ARCHITECTURE

This section details two architectures the team reviewed as baseline architecture for the proposed alternate architecture. The major problems identified in these two architectures became the focal point for the alternate architecture in this paper.

3.1. HEFT Baseline Architecture

NASA has considered crewed missions to NEOs in the past, although it has not yet seen any of these proposed concepts to fruition. The Human Exploration Framework Team (HEFT)[9] designed a baseline architecture and project schedule that utilizes the Space Launch System (SLS) heavy lift vehicle to send a three person crew to a NEO, which the team used as a reference architecture and for comparison. The architecture requires three heavy lift vehicles to launch all mission components. The focal point of the architecture is a Solar Electric Propulsion (SEP) module that, over 339 days, would boost mission elements to Earth-Moon L1. A cryogenic propulsion stage would boost the crew to L1 and another would deliver the crew part way to the NEO. A SEP stage would provide the rest of the thrust needed to arrive at and return from the object. Astronauts would arrive in a Crew Exploration Vehicle (CEV) and live and work in a Multi-Mission Space Exploration Vehicle (MMSEV) and Deep Space Habitat (DSH).

This architecture is appealing due to the low number of launches required; however it is plagued with three major problems: architecture development cost, development and operation schedule, and mission reliability and safety.

3.1.1. Development Cost

Developing all the systems required, especially the heavy lift vehicle, is prohibitively expensive. The entire life-cycle cost of the SLS is estimated to be almost $54 billion,[9] and will cost an average of over $7 billion per year to develop and operate, as shown in Figure 2. This is a significant fraction of NASA's yearly exploration budget, which is estimated to be somewhere between 3 to 4 billion dollars in the near future.[10] At this funding, it becomes difficult for NASA to afford to launch the SLS while also developing and building other mission elements, such as the CEV, MMSEV, and DSH. The current HEFT cost estimate assumes the cancellation of the International Space Station (ISS) program as well as increased NASA funding for exploration system. Without these increases, it is simply not economically possible for NASA to achieve its objective of sending human to an asteroid.

3.1.2. Development and Operation Schedule

The proposed Solar Electric Propulsion (SEP) device has an extremely low thrust when compared to traditional chemical systems. This low thrust leads to

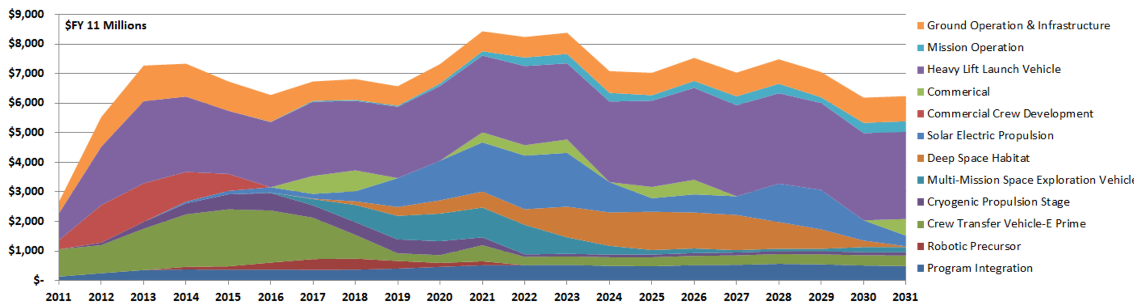


Figure 2: Current Human Exploration Framework Team Cost Estimate for Manned Mission to Near Earth Asteroid[9]

long mission durations for any payload utilizing the SEP. The entire mission would take over five years of in space time to complete. This extended time frame could lead to logistical issues with scheduling and the high cost of operations during this period. The development schedule itself is also much too slow for the target time frame; because of the enormous development cost required by SLS, the DSH's development has been pushed so far back that it will not be ready by 2025.

3.1.3. Mission Reliability and Safety

In addition to financial problems, the reliability of this architecture is also questionable. Prior to 2025, the SLS Block 1A is scheduled to have undergone only three flights (assuming one launch per year), so the system will not yet have reached its inherent reliability. Launch vehicles typically require approximately 20 flights before they reach the inherent system reliability.[11] The SEP will also have gone on similarly few flights and may not have proved capable of the year it is expected to operate. Flying these mission-critical components so few times before a human mission increases the risk of the overall architecture.

The long mission duration requires unreasonably high reliabilities for the various mission elements, including life support systems, to achieve an acceptable probability of mission success. Lastly, this architecture does not include any amount of radiation protection other than what is given by the habitat, which combines with the long duration to pose a significant health risk to the crew and the probability of overall mission success.

3.2. Asteroid Capture Architecture

Recently, NASA has recognized a few of the problems listed above and proposed an alternate mission, in which a SEP powered spacecraft would "catch" a very small asteroid and ferry it back to Lunar orbit. Astronauts would then launch aboard an SLS and explore the asteroid from a closer vantage point. This mission is short-sighted, as it does little to validate technologies needed for crewed long-duration spaceflight and targets a harmless < 20 m diameter asteroid. The mission would also require over six years to collect the asteroid and will not be ready prior to 2025. Finally, the architecture also would require SLS to send the astronauts aboard the CEV to visit the asteroid. This new architecture prunes out the DSH and the MMSEV to help bring the project under budget, at the expense of studying a less scientifically valuable target and failing to advance the in space technologies needed for long duration human spaceflight to more exciting destinations. The team therefore submits the Commercial Core Stages for in space Propulsion (CCS-ISP) architecture as a method of realizing technology development, science goals, and fiscal responsibility.

4. MODELING & SIMULATION

4.1. Trajectory

Ascent and in space trajectories were computed using the Stochastic Program for Optimizing Trajectories (SPOT), an in-house trajectory program that uses Particle Swarm Optimization (PSO) to select the trajectory that minimizes the required system performance. This program was used to assess the performance of the architecture proposed in this study. Launch performance was modeled to determine the feasibility of placing a core stage into orbit and in-space performance was modeled to check if the core stage would be capable of pushing all mission elements to the NEO, as discussed in Section 5. Figure 3 details the program's structure. Given an initial condition, the equations of motion are propagated until a final state is reached (here, the required orbital velocity was used). SPOT contains many modules that help to increase the accuracy of its solution, including varying the thrust with altitude, using realistic aerodynamics, and performing rocket staging. SPOT is unique from other trajectory programs in its treatment of rocket guidance and optimization.

SPOT simplifies the optimal control problem by constraining the rockets angle of attack using cubic Bezier curves. Numerically, the cubic Bezier curve is computed by selecting four points in $\Re^2$, designated

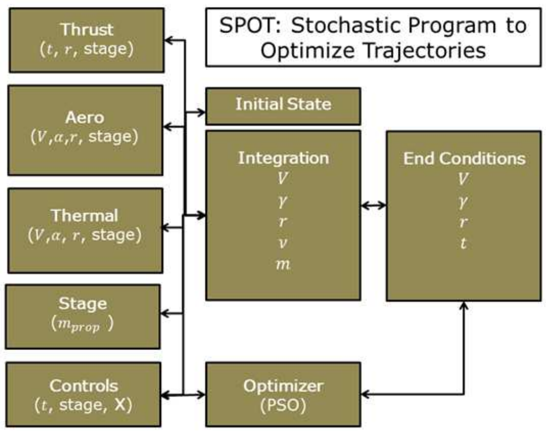


Figure 3: Stochastic Program for Optimizing Trajectories Algorithm Breakdown

P_{0-3}. The cubic Bezier curve is a linear combination of two quadratic Bezier curves. Written explicitly, a point on the curve given the parameter $t \in [0, 1]$ is found using the following equation, from Reference 12:

$$\begin{aligned} P(t) = &(1-t)^3 P_o + 3(1-t)^2 t P_1 \\ &+ 3(1-t)t^2 P_2 + t^3 P_3 \end{aligned} \tag{1}$$

In practice, P_0 is always constrained to zero (corresponding to the starting time of the simulation) and P_3 is set as the maximum simulation time. All other coordinates are allowed to vary in the optimization process.

SPOT uses a PSO algorithm to optimize trajectories. PSO is a collection of simple agents that interact to form a collective intelligence. About 30 such agents seems to be the optimal number.[13] PSO is an iterative algorithm that runs until some convergence criteria is met. In this study, the algorithm was run for a maximum of 500 iterations, but was terminated early if the solution did not improve for 100 iterations and the coefficient of variation was sufficiently low (less than 10^{-7}). The coefficient of variation is defined as the ratio of the standard deviation to the mean and was evaluated for the 10 best particles only. The list of the top 10 particles is continually updated with a merge sort algorithm. Smaller values of the coefficient of variation indicate a more tightly converged swarm.

4.2. Subsystems

To size the solar cells of the mission elements in the CCS-ISP architecture, it was necessary to model their performance over the duration of the mission. Determining the power requirements in daylight and eclipse were essential in defining the overall power requirement that the solar array must meet. The total solar array power requirement was determined by accounting for power transfer efficiencies, power required in daylight/eclipse, and time spent in daylight/eclipse. Using a conservative 28% energy conversion rate for the selected XTJ[14] solar cells, the beginning-of-life solar cell power output was calculated. Once this "theoretical best" beginning-of-life power output was calculated, one must account for the manufacturing and operational inefficiencies that will be experienced, which will decrease actual solar cell energy conversion efficiency. The inefficiencies that have been accounted for include packing efficiency, temperature efficiency, shadowing effect, Sun incidence angle, and life degradation over the lifetime of the mission.[15] The end-of-life solar array power output was calculated after accounting for the performance-reducing effects mentioned above. As a conservative measure, the calculated "worst case" end-of-life solar array power output was used to size the final solar array area and mass.

5. CCS-ISP ARCHITECTURE

The CCS-ISP architecture encourages a paradigm shift in space exploration. In an age of constrained budgets, the only viable way to construct a sustainable space program is to foster not only innovation but also affordability.[2] By including commercial enterprises in this mission and encouraging competition, NASA can realize huge cost savings and schedule improvements over the old cost-plus contract model.

The CCS-ISP architecture makes use of off-the-shelf and near term commercial products and uses an innovative in space propulsion stage to reduce development and mission times when compared to the HEFT architecture. The architecture concept of operations is shown in Figure 4. First, a Falcon Heavy is launched to orbit, which remains in a 407 km parking orbit to be refueled. Ten additional Falcon Heavy flights deliver propellant to the orbiting vehicle via cryogenic propellant transfer. The next two Falcon Heavy flights deliver the mission payloads, tabulated in Table 3, and Figure 5 shows the payload manifest for the two flights. After the elements are all in place, a Falcon 9 delivers the crew aboard the Dragon capsule to the now assembled spacecraft. The low payload of the second rocket could be launched on a smaller rocket from another carrier, which would allow the last two flights and the crew flights to proceed faster. However, the nominal schedule is left as is to provide for contingency in case a propellant flight fails and more propellant flights are required to make up for the lost spacecraft.

After the elements are assembled on orbit, the mission proceeds as in HEFT, with the SEP transfers replaced with burns from the Falcon Heavy core and upper stage. At the conclusion of the mission, the Dragon capsule performs a direct entry at Earth to return the crew. A summary of the the performance requirements of the in space maneuvers is tabulated in Table 4.

The key components of the architecture are listed below:

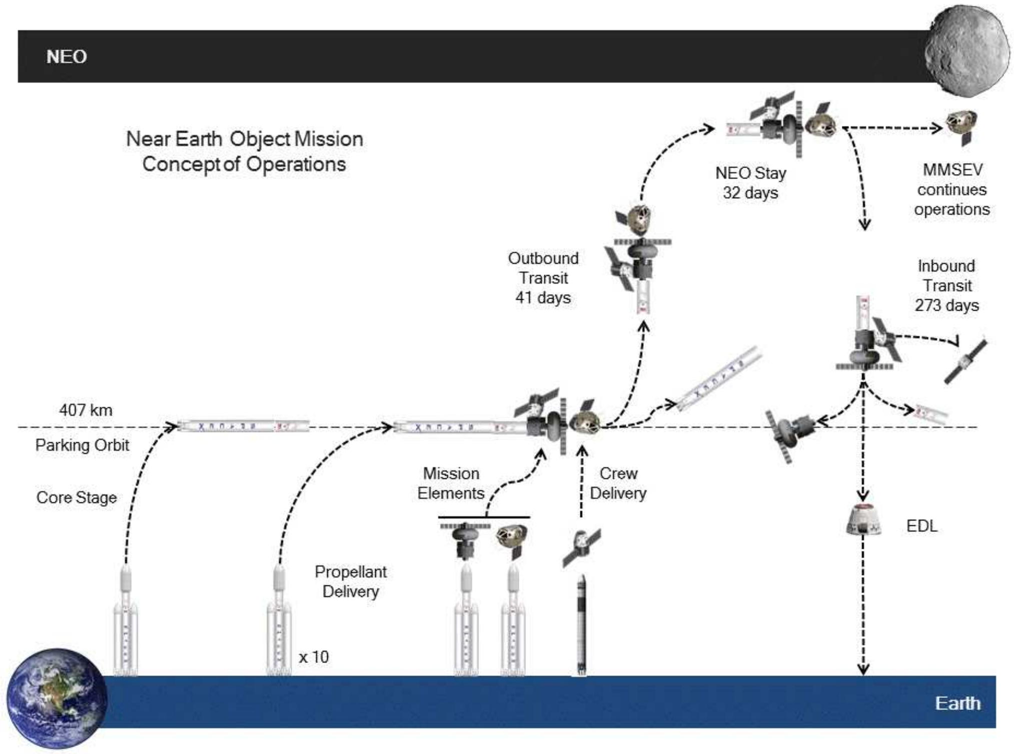


Figure 4: CCS-ISP Architecture Concept of Operation

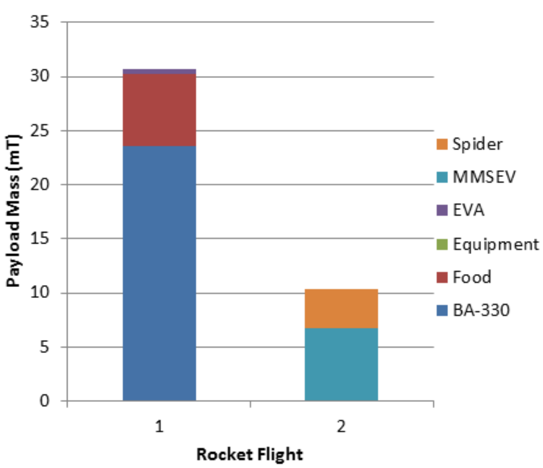


Figure 5: Payload Manifest for Mission Element Launches

- A commercial ascent vehicle core stage is used as the in space propulsion system for both outbound and inbound burns
- This core stage is refueled by commercial launch vehicles, separated from the mission-critical elements and crew launch, to increase reliability by decoupling propellant launches from the success of the mission

Table 3: CCP-ISP Architecture Payload Manifest

Item	Mass (kg)
Elements Taken All the Way	
Inflatable Habitat	23,600
Science Equipment	320
Crew	450
Power & Thermal Management	2,895
Extra-Vehicular Activity Equipment	435
Crew Capsule & Service Module	6,000
Elements Left at Destination	
MMSEV	6,700
Spider	3,560
Consumables	
Outbound	6,620
Return	5,280
Asteroid Sample Retrieval	
Sample	50

- A combination of NASA and commercial hardware is used to perform the in space and destination missions
- Savings realized from the removal of the SLS, CEV, and solar electric propulsion systems are used to improve the program's schedule and budget, while permitting investment into advanced technologies for future missions
- The architecture is extensible to future destinations such as Mars and beyond

Table 4: CCP-ISP Architecture Performance Requirements for in space Maneuvers

Maneuver	Payload Mass (kg)	ΔV (km/s)	Propellant Remaining
Earth Departure	50,300	4.285	98.67%
NEO Arrival	49,000	0.624	70.44%
NEO Departure	37,400	1.378	29.33%

5.1. Propulsion System

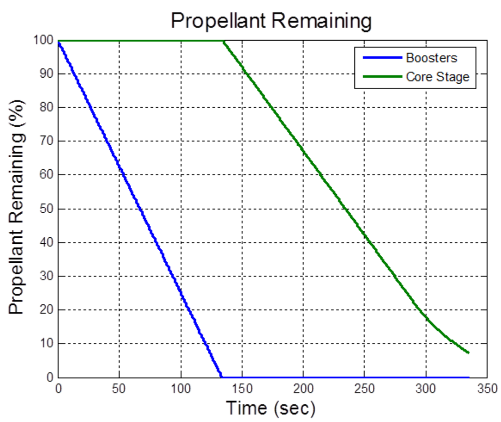


Figure 6: Propellant Depletion During Falcon Heavy's Ascent to Orbit with SPOT Simulated Ascent Trajectory

Rather than developing a new in space propulsion stage, our proposed architecture relies on the use of existing commercial rocket stages to reach NEOs. Due to its payload capabilities and development progress, the SpaceX Falcon Heavy launch vehicle was identified as the most promising commercial launch vehicle and in space stage. Figure 6 shows the computed propellant fill level for the Falcon Heavy during an ascent to a 190 km circular orbit; a small additional burn would boost the stage to the 407 km staging orbit. This stage would stay in orbit around Earth while additional commercial rockets deliver propellant. Once the core stage is completely filled, it will be ready to travel to a NEO. The Falcon Heavy's low inert mass fraction allows more payload to be delivered to the asteroid, and the use of RP-1, which has a much higher boiling point than hydrogen, lessens the need for aggressive cryocooling in orbit.

The use of commercial launch vehicles provides advantages over the standard government models, these includes:

- Decreased operations and maintenance costs to NASA
- Increased reliability due to decoupling of propellant flights from mission hardware flights
- No DDT&E costs paid for by NASA for an upper stage or heavy lift vehicle

Table 5: Commercial Launch Vehicle Summary[16,17,18]

	Payload LEO	Nominal Launch Rate	Launch Cost FY12
Delta IV H	23 mT	3 / Yr	$300 M
Falcon H†	51 mT	6 / Yr	$81-127 M
Atlas V 551	19 mT	4 / Yr	$290 M

In order to bring all desired payloads to Apophis and back, one core stage and one upper stage are both needed in orbit. The first Falcon Heavy flight will therefore deliver the empty upper stage and partially filled core stage into orbit. A modified upper stage with a reaction control system (RCS) is needed to deliver the core stages to their proper orbit. A robotic articulation system such as the Shuttle Remote Manipulator System (RMS),[20] commonly known as the "Canadarm", will also be needed to grab mission components and place then next to the main core stage. This RMS will be launched aboard the first rocket.

Once the initial core and upper stage have achieved orbit, the now empty stages will need to be filled by tanker vehicles. The near-term expected commercial launch capability is summarized in Table 5. The nominal launch rate is determined by the past and future launch manifests. Currently, the Delta and Atlas family of launch vehicle is averaging about three to five launches per year, or roughly a launch every 90 days, and launch manifest indicates the same rates for the foreseeable future. The Falcon 9 and Falcon Heavy's manifest indicates a target of eight launches per year, which averages to roughly a launch every 45 days.

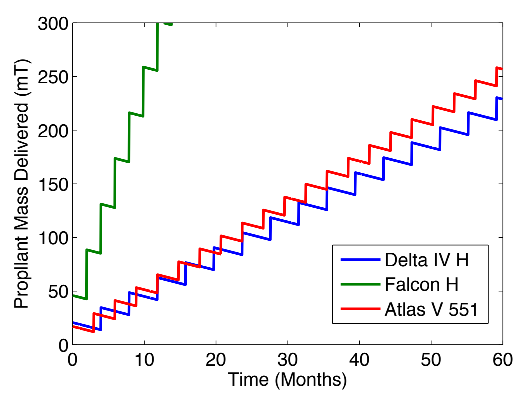


Figure 7: Propellant Build Up Using of Commercial Launch Vehicles with No Active Cryocooling

Using the payload and nominal launch rates, the propellant build-up rate can be computed and is shown in Figure 7, which plots the build-up rates utilizing the three launch vehicles to Low Earth Orbit (LEO) with no active cooling. Figure 8 shows the propellant build-

† In Development, First Flight Scheduled for 2014[19]

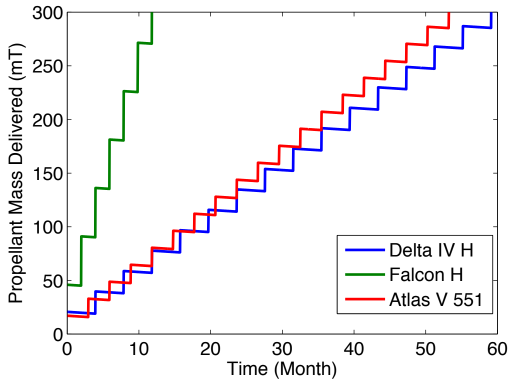


Figure 8: Propellant Build Up Using of Commercial Launch Vehicles with Active Cryocooling

Table 6: Average Propellant Build-up Rates to LEO

	No Cryo	Cryo	
Delta IV H	3,500	4,810	kg/month
Falcon H	21,600	22,900	kg/month
Atlas V 551	4,070	5,350	kg/month

up rate with active cryocooling capability. The propellant build-up rate is also summarized in Table 6. These build-up rates assume launch rates of three Deltas per year, four Atlas per year, or six Falcons per year. The payload is assumed to have a propellant mass fraction of 0.90, meaning 90% of the payload capacity consists of propellant.

Although this missions crew will be in space for less than a year, propellant buildup must start in excess of one year before the mission is to launch. Assuming the Falcon Heavy has a nominal flight rate of one flight every 45 days, the mission resulting schedule is shown in Table 7.

Table 7: Mission Schedule Assuming 45 Day Launch Interval for Falcon Heavy

Mission Days	Event Description
-550	Initial core stage launch
-505	Propellant launch for core
-460	Propellant launch for core
-415	Propellant launch for core
-370	Propellant launch for core
-325	Propellant launch for core
-280	Propellant launch for core
-235	Propellant launch for core
-190	Propellant launch for core
-145	Propellant launch for core & upper stage
-100	Propellant launch for upper stage
-55	Habitat and supplies launch
-10	Exploration vehicle launch
0	Crew launch
+41	Asteroid arrival
+73	Asteroid departure
+346	Earth entry

5.2. Crew Systems

The HEFT architecture calls for the development of an MMSEV, CEV, and DSH. The CEV allows the crew to ascend and descend through the Earth's atmosphere, the MMSEV to explore the NEO, and the DSH to live comfortably and safely during the long outbound and inbound trips. This configuration of three main mission elements is logical and does not require any modification. The CCS-ISP architecture will also use three separate elements for crew ascent and descent, long-term transportation, and exploration of the NEO. However, cost savings are projected to result from utilizing commerical crew launch capability such as SpaceX's Dragon capsule, rather than developing separate NASA systems.

5.2.1. Crew Habitat

Whereas the HEFT architecture proposes NASA develop a new inflatable habitat, CCS-ISP advocates the use of a readily available commercial habitat from Bigelow Aerospace.[21] Bigelow Aerospace has been developing inflatable space habitats for nearly a decade and has already flight-tested two systems (Genesis I and II). The habitation modules that NASA has already developed on the International Space Station are not intended to be stand-alone units and would require significant development to prepare them for deep space travel. However, Bigelow's latest system, the BA 330, is intended to function as an independent unit. Bigelow Aerospace sells these units equipped with an Environmental Control and Life Support System (ECLSS), an independent power system (solar arrays and batteries), as well as propulsion and avionics to aid in docking. The BA 330 is already under development with a slated flight test date of 2014, putting it ahead of NASA's DSH system. Additionally, the BA 330 will have nearly three times the volume of NASA's proposed DSH but will have 3,000 kg less inert mass Recently, Bigelow Aerospace was awarded a $17.8 million contract to develop a large inflatable module for the ISS , which is slated to nearly triple the pressurized volume of the ISS. This development makes the BA 330 a promising selection for a deep space mission.

5.2.2. MMSEV

The Multi-Mission Surface Exploration Vehicle is a crewed surface exploration vehicle already under development by NASA. It will weigh an estimated 6.7 mT and can support two astronauts for up to 14 days. With frequent resupply trips to the DSH, the vehicle would be able to support the astronauts for even longer, and allow for crew rotation with the habitat. This MMSEV is assumed to be the same as designed for the HEFT mission, and no further changes are made.

5.2.3. Crew Delivery

Commercial Crew Development (CCDev)eliminates the need to build a CEV because any of several commercial vehicles[22,23,24] can instead be used. Although NASA is progressing with the development of the Orion capsule, a commercial CEV will be less expensive. Additionally, Space X is already taking the steps to manrate their flight-proven Dragon Capsule, which eliminates the worry of not having a CEV ready in time. The system, if capable of high-speed reentry, can handle the thermal load of a direct entry into the atmosphere from a NEO. This capsule will have room to take up to seven astronauts to the ISS when completed and will have the life support capability to sustain the astronauts for very short trips. The capsule must be taken to the asteroid and back due to the high entry speed of the spacecraft upon Earth return. Descending directly into the Earth's atmosphere eliminates the need to perform a costly circularization burn at the end of the mission.

5.3. Asteroid Surface Systems

5.3.1. Spider

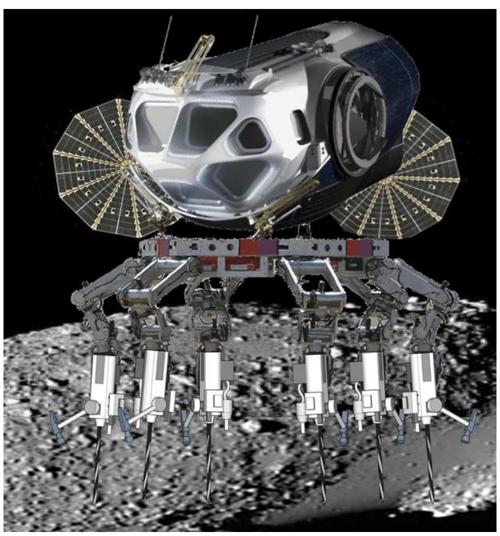


Figure 9: Robotic Surface System Spider

A robotic system called the "Spider" was designed in order to improve astronaut mobility and to allow for continuous robotic operations at Apophis after the crew departs for Earth. The Spider is a hexapod system based off Jet Propulsion Laboratory's All Terran Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) system,[25] which was designed to promote habitat mobility on the Lunar surface. Each leg of ATHLETE can articulate in roll, pitch, and yaw. Such a system would allow the MMSEV to grapple with the asteroid for an extended period of time, as well as allow location changes without the use of propellant. The MMSEV can continues remote operations after the crew departs, allowing for further exploration without expending consumable resources.

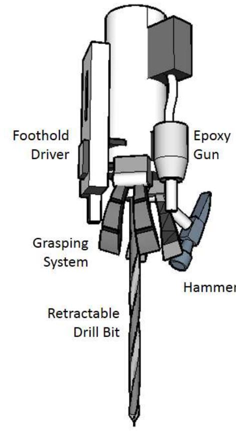


Figure 10: Spider Leg Drill and Attachment System

To operate in the very low-g environment of the Apophis, the ATHLETE system's legs are modified to replace the wheels with grappling hooks. Each leg also features a magazine of expanding bolts, a drill, and a piston hammer, as shown in Figure 10. Before taking a step, the leg will drill a small hole in the asteroid, then use the piston hammer to install the expanding bolts. In hard rock, this will be sufficient to place a permanent bolt in the asteroid that can be reused as a foothold by both the Spider and the crew while on EVA. For medium and soft rock, the addition of an adhesive will keep the bolt in place. The top of the Spider will remain flat and feature a docking mechanism for the MMSEV. This system provides a few major benefits, including:

- Completely electric mobility system minimizes MMSEV reaction control system use during crew operations
- Autonomous installation of footholds for the crew
- MMSEV and Spider can continue operations long after the crew has gone because there is no need for propellant refill
- Allows the system to explore a large portion of the asteroid

This system would be similar in size to the ATHLETE 2 prototype but would need to be more massive due to the following components:

- Additional drill, hammer, foothold loader, and adhesive dispenser on each leg
- Docking mechanism for the MMSEV on the top of the body

Table 8: Spider Surface System Mass Breakdown

	Mass	
ATHLETE-2[25]	1,440	kg
MMSEV Docking Mod	400	kg
Power System	300	kg
Drill, Hammer, Leg Segment	600	kg
Mass Groth Margin (30%)	820	kg
Total	3,560	kg

Table 9: Potential EVA Sampling Tool List[28]

Tool	Mass (kg)
Contact Soil Sampling Device	0.5
Core Tube	0.3
Drill	13
Hammer	1.5
Scoop	0.4
Tongs	0.2

- Solar cells and extended battery capacity for system operation during solar shadow

These changes adds additional mass to the Spider system that must be accounted for in the overall system architecture. A summary of these additions, and the associated mass is shown in Table 8. With the changes made to the ATHLETE 2 system, and a mass growth margin of 30% the spider system is estimated to be 3,560 kg. This mass represents a small portion of the overall payload required for asteroid exploration, and the performance capability of the Falcon upper stages is more than capable of handling the payload requirement.

5.3.2. Crew Extra-Vehicular Activity

Due to the complexity of landing and latching onto the surface of Apophis, it is desirable to make each surface mission several days in duration. This fits within the capability of the MMSEV, which is designed to support two astronauts for up to 14 days. The MMSEV would transport the surface crew and equipment to a selected landing site. Given Apophis' low rotation period of 30.4 hours (equating to a maximum surface velocity of about 0.01 m/s), rendezvous with its surface is expected to be straightforward. Although a highly irregular shape could make some regions of Apophis inaccessible, recent observations suggest that Apophis has a simple ellipsoidal shape. Additionally, Apophis' relatively low mass of 2.4×10^{10} kg means that gravitational effects are essentially negligible.[26] This avoids stability problems that could be caused by an irregular mass distribution.[27]

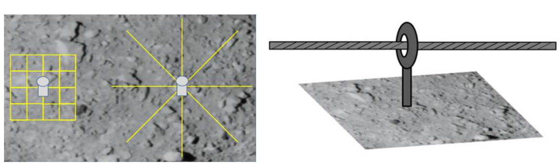


Figure 11: Attachment Structural Support Notional Example

Latching onto the surface of Apophis presents one of the most significant challenges of the sample collection mission due to the unknown composition and structure of Apophis. According to a recent spectral analysis of Apophis, it is most likely composed of chrondite, a stony material.[26] Although chrondite is well suited for holding anchor points, Apophis is also thought to have macroscopic porosity due to its low gravity, making it a “pile of rubble” instead of a compacted body.[26] This presents a unique set of challenges for the anchoring system; a variety of drill bits would be needed to handle unknown terrain features. The MMSEV would use its maneuvering thrusters to attach to the surface with its Spider system and aid in the creation of Extra-Vehicular Activity (EVA) attachment points. The flexibility of the Spider's drilling and attachment system avoids the complexity of creating anchor points during an EVA. The astronauts would need a network of attachment points to use while sampling the surface because many tools, such as drills and coring samplers, would require strong anchors to react against while they operate. Depending on the desired breadth and resolution of sampling at each landing point, many different schemes of attachment points could be used, as shown in Figure 11.

For the surface exploration and sampling, the equipment used in the Apollo missions would provide a starting point for sampling tools. The primary difference between Apollo and asteroid sampling tools is that the asteroid tools would not have to be designed for use by astronauts who must remain upright. The extremely low gravity of Apophis would allow astronauts to put themselves in a prone position relative to the surface, reducing tool size and complexity. However, the low gravity of Apophis would introduce challenges as well. All sample collection tools would have to be designed to minimize unnecessary disturbance and dislodging of surface material to avoid hazards and obstructions. Using the Apollo sample collection tool list as a starting point, the recommended tool list is shown in Table 9. Due to the low gravity environment and rocky composition, drills and core sampling tools would be the safest and most fruitful.

In addition to asteroid-specific sampling tools, a new class of space suits would be needed. These suits could be heavily based on current EVA suits used on the ISS to be cost-effective. Current EVA suits are already fit for microgravity operations, but would require some modifications to the outer layers for contact with a rocky surface. This would include added resistance against abrasive particles as well as the addition of reinforcement and non-skid pads on the knees and toes to promote movement over the asteroid surface.

Surface exploration of Apophis will pose additional threats to the crew not previously experienced on Lunar or ISS EVAs. The most significant difference from either of these previous missions will be the presence of asteroid regolith in a low-gravity environment. Any sampling activities have the potential to stir up dust and rocks that would have the potential to hamper visibility or cause damage. Significant development in surface sampling tooling would be required for this mission. Additional danger in surface exploration could arise from the irregular shape and rotation of Apophis. An astronaut or exploration vehicle tethered to the surface would experience unpredictable accelerations relative to the surface of the asteroid. Mitigating risks in this area would require development of unique training and tethering equipment

5.4. Crew Health & Safety

Paramount to the success of any space mission is the health and safety of the crew. Many of the potential threats to crew safety in a trip to a NEO have been thoroughly studied on-board the International Space Station. By constraining mission time to one year, most potential problems related to human health during extended periods in microgravity are well understood. The trip to a NEO would be well within the longest duration spent in microgravity (438 days). The only difference between ISS and NEO missions in the human health aspect is that the crew on a NEO mission would have no chance to return to Earth in the event that they became seriously ill or injured. This would require the development of compact, lightweight medical devices to give the crew a higher level of medical capability than currently available on the ISS.

External threats to the spacecraft would be very similar to those posed to the ISS with a few differences. Damage from spacecraft charging and subsequent arcing due to space plasma is understood from ISS and robotic missions. However, the long EVAs necessary for surface exploration would increase the chance of the crew receiving damaging doses of radiation from solar activity. Solar particle events are difficult to accurately predict; once they occur, astronauts only have approximately 30 minutes to seek shelter from the energetic particles.[29] Current space suits do not have enough shielding to protect humans from these particles, which motivates the use of a vehicle such as the MMSEV to support EVA. in space radiation protection remains an active concern for future human space exploration architectures.

The BA-330 inflatable habitat recommended for this asteroid mission will be equipped with Orbital Technologies Corporation's (ORBITEC) Environmental Control and Life Support Systems. Bigelow Aerospace recently partnered with ORBITEC to provide efficient and sustainable life support systems suited for long duration missions. The equipment ORBITEC will provide is similar to many systems currently flow on the ISS, but with improvements focused on sustainability. A summary of these systems is provided in Table 10.

6. RESULTS & DISCUSSION

6.1. Architecture Cost

The CCS-ISP architecture is both more affordable and available sooner (by 2025), than the HEFT architecture. These costs savings result from the use of commercial systems for the in space habitat, crew capsule, and launch vehicle/in space stage, as well as the elimination of solar electric propulsion, the CEV, and the SLS. Even the added elements required by the CCS-ISP architecture are not expected to cost more than the savings realized from the above changes.

The HEFT architecture's costs are shown in Figure 2, as derived from the cost data in Reference 9. These costs were expected to be spent over twenty years, with the mission completed by 2031. The total architecture will cost approximately $136 billion (assuming the 2011 and 2012 cost has already been spent), with an average annual cost of almost $7.1 billion and a peak cost of $8.5 billion. These costs outpace the NASA human exploration budget, yielding an infeasible mission.

Costing of the CCS-ISP architecture (see Figure 12) began with these same cost estimates for the common elements, then adjusted them for the commercial elements introduced. The Bigelow Aerospace 330 habitat was costed from data in Reference 30, with the price being estimated as that of a full habitat for two entire years, doubled for margin. The eleven launches of the Falcon Heavy and one launch of the Falcon 9 were costed from the price given in Reference 16, spread over the three years leading up to the 2025 mission date. The cost of the Dragon capsule was estimated from the costs of the ISS resupply contract awarded to SpaceX in 2008.[31] The ATHLETE-derived Spider was costed from NASA estimates for the ATHLETE, quadrupled to account for the additional development required for the architecture's particular needs.

In lieu of developing the cryogenic stage (which is replaced by the Falcon Heavy's previously developed stage), money is spent on the development and implementation of the relevant cryogenic storage and transfer technologies. Finally, costs previously budgeted beyond 2025 (the mission launch date) were spread over the previous years, excepting operations costs during 2026 and 2027 (mission operations). The total cost of this architecture is estimated at $46 billion, with an average annual cost of $3.3 billion and a peak cost of $4.0 billion. These costs are in line with NASA's human ex-

Table 10: Environmental Control and Life Support System Components

Component	Description
Cabin Atmosphere VOC Monitoring	Real-time monitoring of composition and properties of cabin atmosphere
Hydrogen / Oxygen Generation	Produces Hydrogen and Oxygen gases through water electrolysis
Water Processing and Storage	Recycles water into a potable form
Active Thermal Control	Single-loop fluid system to control temperature of cabin atmosphere
Gaseous Trace Contaminant Removal	Carbon filtration and catalytic oxidation system to remove unwanted gases from cabin atmosphere
Internal / External Lighting	Robust, efficient, and customizable lighting system
Pressure Control and Supply	Maintains cabin total pressure and partial pressure of N_2 and O_2
Temperature Humidity and Ventilation Control	Removes excess heat and moisture while mixing cabin gases
Carbon Dioxide Removal	Scrubs CO_2 from cabin atmosphere for venting or recycling

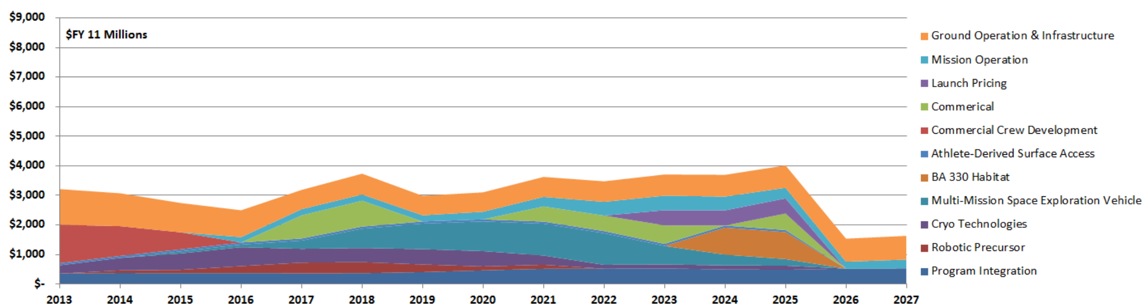


Figure 12: Cost Spread for Manned Exploration Mission to Near Earth Asteroid using the CSS-ISP Architecture

ploration budget, and the architecture is economically feasible.

With these savings, even significant cost overruns still yield a more affordable architecture. Additionally, other technologies that could enhance capability down the road, or extend access to Mars or other destinations, can be paid for using the money not spent on the removed systems.

6.2. Architecture Reliability

The CCS-ISP architecture is more reliable than the HEFT architecture. By 2025, the SLS Block I is scheduled to have flown twice and the Block 1A to have flown three times, assuming NASA can finance a launch rate of one per year. The newly developed SLS system suffers from the issue of reliability growth, or the infant mortality aspect of unreliability. The reliability of any new launch vehicle is highly uncertain and can only be proven with a large number of demonstrated flights. Reliability growth was a major concern during the Apollo program,[32] and the estimate of initial probability of success for the first few lunar mission was very low. This is demonstrated by the initial reliability assessment of the various stages of the Saturn rocket shown in Figure 13.

This reliability growth trend can also be observed by examining actual launch data compiled from var-

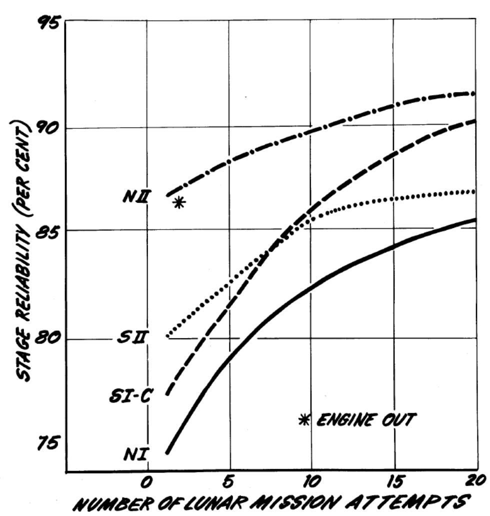


Figure 13: Reliability Growth Estimate of Various Stages of the Apollo Program, reproduced from 32

Table 11: Direct Cost Comparison between HEFT and CCS-ISP Elements Starting in 2013

HEFT Element Costs, FY13		CCS-ISP Element Costs, FY13		%Δ
Program Integration	\$8,802	Program Integration	\$6,885	-22%
Robotic Precursor	\$1,703	Robotic Precursor	\$1,703	- -
Crew Transfer Vehicle-E Prime	\$13,282	Dragon Capsule	\$258	-98%
Cryogenic Propulsion Stage	\$4,727	Cryogenic Fluid Management Technology	\$4,721	- -
Multi-Mission Space Exploration Vehicle	\$6,315	Multi-Mission Space Exploration Vehicle	\$6,315	- -
Deep Space Habitat	\$9,617	BA 330 Habitat	\$1,825	-81%
Solar Electric Propulsion	\$14,875	ATHLETE-Derived Surface Access	\$914	-94%
Commercial Crew Development	\$6,764	Commercial Crew Development	\$6,764	- -
Heavy Lift Launch Vehicle	\$51,028	Commercial Launch Purchase	\$1,718	-97%
Mission Operation	\$3,175	Mission Operation	\$3,705	+17%
Ground Operation & Infrastructure	\$15,412	Ground Operation & Infrastructure	\$12,033	-22%
TOTAL	**\$135,700**	**TOTAL**	**\$46,513**	**-66%**

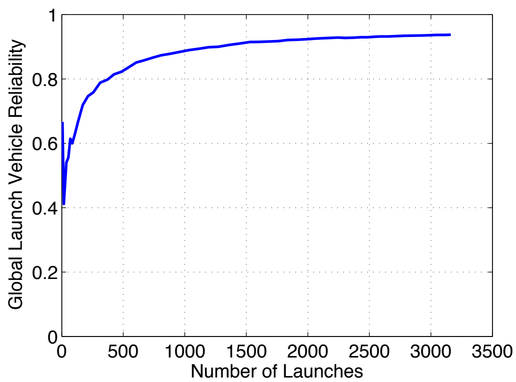


Figure 14: Total Global Launch Vehicle Reliability Growth Data of Actual Flights of Major Launch Vehicles between 1957 and 2012

ious public sources. Launch data for the Delta II, Delta IV, Atlas, Falcon, Japan's H-II, Europe's Ariane, China's Long March, and Russian's Proton and R-7 family as well as the Space Transportation System were compiled from 1957 to 2012 from a variety of sources,[33,34,35] and the reliability growth of the global launch market is shown in Figure 14. The data also confirms the 94% overall success rate quoted by Guikema.[34] Reliability growth was also discussed in detail by Morse[11] and Young.[36]

These data show that a system that has been proven with actual flight vehicles will ultimately have higher reliability compared to an infant system. Per Morse's model,[11] the reliability of the first 10 flights of a new launch vehicle is well under 0.80, and won't reach 0.90 until around 50 flights. For a new heavy lift launch vehicle that launches once every two years, it would take a century to reach this proven reliability. In comparison, a new Falcon Heavy commercial launch vehicle may reach this proven reliability in less than a decade with its planned launch rates, especially if a depot architecture exists to create demand for commercial launch vehicles.

For a manned mission starting in 2025, historical reliability growth data for launch vehicles shows this is not nearly enough time for the SLS to reach its true reliability plateau. Using existing commercial systems with a high launch rate allows these systems to approach their maximum reliability. Additionally, if one of the propellant flights fails, the replacement costs for another flight are much less than those of an SLS carrying both propellant and mission elements. Finally, this system also decouples propellant delivery from the launch of the mission-critical elements and the crew.

6.3. Architecture Technologies

The CCS-ISP architecture will require research and innovation in several areas to be successful. However, all of these technologies have already been identified by NASA as critical technologies for a sustainable manned space program, and all have already been awarded at least modest investment. Table 12 outlines the current state of critical technologies for a NEO mission along with the Technology Rediness Level (TRL) and identifies where improvement is needed. The most critical technologies for the CCS-ISP architecture pertain to management of cryogenic propellants.[37] Current experimentation in this area has been limited to either ground tests or short-duration missions. Low-g cryogenic fluid transfer, which will be required to pump liquid oxygen from the propellant delivery vehicles to the parked core stage, is difficult to test on a large scale. Research will also be needed in cryogenic fluid management to prevent boil-off in orbit. Although long-term storage of cryogenic fuels is a topic of significant interest, no long-duration flight tests have been performed. Lastly, there is currently no working method to measure the propellant fill level of a tank in space, although some concepts have been tested in a laboratory environment. This will be critical for monitoring the propellant during the year the in space stage is being filled.[44] In all, cryogenic-related technologies will require the most significant advancements to bring the CCS-ISP (or any deep-space) architecture to fruition.

Human-health systems, such as life-support system,[39] habitat,[30] on orbit medical capability,[40] and

Table 12: Technology Description of CCS-ISP Based Exploration Architecture

Technology	TRL	Description
Cryogenic Fluid Transfer[37]	4-6	Essential for refueling core stages in LEO. Not yet demonstrated in a relevant environment, demonstrator mission planned by NASA[38]
Zero-Boil-Off of Cryogenic Fluids	4-5	Preventing boil-off reduces the number of flight needed to fill the core stage. Cryocoolers for oxygen but keeping hydrogen cold requires more energy
Low G Liquid Gage	5	Some concepts for measuring liquid levels in microgravity have been demonstrated in a relevant environment but they are not yet used routinely. Critical for monitoring the fill level of the parked core stage.
in space Core Stage Propulsion	5	Restarting a launch vehicle core stage in orbit has never been tested. Although they are designed for atmospheric flight, if the engines have been designed to be restarted this should not be a critical issue. To improve Isp, some core stage engine nozzles could be elongated with a nozzle attachment.
Life Support and Habitation[39]	8	Most technologies developed for long-duration stays in the ISS would transfer directly to a one year asteroid mission.
Exploration Medical Capability[40]	6	Some space-grade equipment needed to improve beyond ISS capabilities such as surgical and dental tools
Space Radiation Protection[41]	3	Some inflatable habitation systems (Bigelow) have been shown to have as good or better radiation protection than the ISS. Additionally, deep space radiation is well understood from robotic missions
Autonomous Systems[42]	8	Although now in use routinely around the ISS, Autonomous Rendezvous and Docking is a new and rapidly progressing technology. Some work needs to be completed in outfitting propellant tankers with a system to successfully guide it to a core stage and autonomously secure fluid transfer values. Sloshing effects and poor lighting may make this process difficult
Advanced Navigation/ Communication[43]	6	New navigation and communication systems are needed to support manned spaceflight beyond LEO and cis-lunar space
Lightweight Materials and Structures	6	Advanced lightweight structural and material concepts are rapidly approaching a state of flight-readiness. The two key concepts proposed here, inflatable structures and composites are both demonstrated technologies. Inflatable structures have been demonstrated on the Bigelow Aerospace Genesis I and II. Composites have been applied in numerous instances in various space applications
Environmental Mitigation	4	For deep space travel, the BA 330 will be rated to meet or exceed the crew protection capabilities of the international space station for radiation protection and micrometeorite impact. For operations at the asteroid surface, data collected from all EVA missions to date will aid in mission planning and equipment design

radiation protection,[41] have been of significant interest since the initiation of human spaceflight. For this reason, current human-health technologies are well-poised to be applied to a NEO mission. All of the human-health technologies needed for a NEO mission have been flight-tested in one form or another, mostly on the ISS. All that remains for these technologies is to customize them for the CCS-ISP architecture and rate them for long-term functionality.

Avionics/communications[43] technology needed for the CCS-ISP architecture is also well within the capabilities of current flight tested systems. Tasks such as autonomous docking and navigation have been successfully demonstrated by the Dragon capsule, as well as other spacecraft. Deep-space communications technology has also been maturing for many decades and would require little development for applicability to a NEO mission.

The majority of the technology needed for the CCS-ISP architecture is not specific to a NEO mission, making CCS-ISP an attractive first step into cis-Lunar manned flight. Only the systems pertaining specifically to asteroid EVA, such as the Spider system and customized spacesuits, are not directly extendable into other cis-Lunar ventures. The versatility of the technology needed for the CCS-ISP architecture permits development of further deep-space missions without a significant technology reboot.

7. CONCLUSIONS

The CCS-ISP architecture is more affordable and reliable than the baseline NEO architecture. These improvements are achieved by replacing key NASA systems with commercial counterparts that do not require the same degree of investment to bring to maturity, along with the use of a launch vehicle whose reliability will be proved out within the mission time line. The savings can either be used as a buffer against cost overruns, or reallocated to development of advanced technologies.

The fundamental structure of this architecture is also extensible to other destinations. The development of on-orbit refueling and the use of commercial stages will permit similarly affordable ventures to the Moon, Mars, and beyond. Additionally, further technical development can facilitate the use of multiple core stages to dramatically boost payload and performance capability: some modification to the Falcon Heavy core and upper stages may permit reattachment in orbit. Such a vehicle could deliver large payloads to future destinations, including advanced active radiation shielding and space power concepts currently too massive to include in any near-term architecture. The use of commercial elements combined with NASA systems permits an affordable, sustainable, and extensible approach to the exploration of NEOs, and paves the way for travel throughout the solar system.

8. EDUCATION & PUBLIC OUTREACH

Beyond the design of a cost-efficient human space exploration mission architecture, the CCS-ISP team is interested in better understanding and preserving our home planet. NASA is a global leader in Earth science and planetary health monitoring, a fact that is sometimes overshadowed in the public eye by its space-related programs. The team chose to visit a local school to promote awareness as part of NASA's education and public outreach mission.

The team traveled to Cooper Elementary School, a Science, Technology, Engineering, and Mathematics (STEM) magnet school in Hampton, VA. Team members visited second grade science classes and read Dr. Seuss's The Lorax, a story of the tragic consequences for a neglected environment. The reading was followed by a discussion of the book's themes and what the students can do to protect our environment, as well as the benefits of Earth observation from space. The discussion ended with an open question and answer session about NASA's role in society as well as life in a STEM profession. To conclude the class session we helped the students construct STEM Notebooks to record their observations. Many choose to draw the NASA logo on the covers (See Figure B.1). In all, the team spoke to seventy enthusiastic and engaging students.

APPENDIX A

Acronym	
Near Earth Objects	NEO
Human Exploration Framework Team	HEFT
Space Launch System	SLS
Solar Electric Propulsion	SEP
Crew Exploration Vehicle	CEV
Multi-Mission Space Exploration Vehicle	MMSEV
International Space Station	ISS
Stochastic Program for Optimizing Trajectories	SPOT
Particle Swarm Optimization	PSO
Commercial Core State for In Space Propulsion	CCS-ISP
Reaction Control System	RCS
Remote Manipulator System	RMS
Low Earth Orbit	LEO
Environmental Control and Life Support System	ECLSS
Commercial Crew Development	CCDev
All Terran Hex-Limbed Extra-Terrestrial Explorer	ATHLETE
Extra-Vehicular Activity	EVA
Orbital Technologies Corporation	ORBITEC
Technology Readiness Level	TRL
Science, Technology, Engineering, and Math	STEM

APPENDIX B

Education & Public Outreach

Figure B.1: Georgia Tech RASC-AL Team's Education and Public Outreach Effort at Cooper Elementary School

APPENDIX C

Compliance Matrix

2013 RASC-AL Compliance Matrix

	Y	N
ALL TEAMS	**Y**	**N**
Is the overall system architecture addressed sufficiently? (It is okay to focus on one specific aspect of the theme or the mission, as long as the project properly addresses all mission aspects and systems from launch through return as well as surface systems and activities).	✓	
Have you addressed reliability and human safety in your design?	✓	
Have you identified the appropriate key technologies and TRLs?	✓	
Have you identified the systems engineering and architectural trades that guide the recommended approach?	✓	
Have you considered how the project would be planned and executed?	✓	
Have you included a project schedule, including a test and development plan?	✓	
Have you included information on annual operating costs (i.e., budget))?	✓	
Will your team faculty advisor be present during the 2013 RASC-AL Forum? *(required)*	✓	
Does your abstract meet the 5 page limitation? *(Abstract)*	✓	
Does your paper fall within the 10 – 15 page limitation? *(Final Paper)*	✓	
NEAR-EARTH ASTEROID (NEA) FLEXIBLE MISSION ARCHITECTURE DESIGNS	**Y**	**N**
Are all systems and technologies available for initial human missions in 2025?	✓	
Does your analysis include launch systems, in-space system, and surface exploration systems, tools, and equipment?	✓	
Have you considered/demonstrated leveraging the SLS?	✓	
Is your robotics system capable of gathering samples from at least 10 cm under the surface, and can it help determine the interior structure and composition of the body?	✓	
Have you examined the potential for these same systems being used for other deep-space human missions?	✓	
Have you considered approaches for evolving the architecture to include reusable elements to enable sustainable solar system exploration?	✓	
HUMAN-FOCUSED MARS MISSION SYSTEMS AND TECHNOLOGIES	**Y**	**N**
Have you developed an innovative technology and/or system approaches that improve astronaut health and safety in at least one of the following categories?		
o radiation shielding and countermeasures		
o exercise systems and regimes		
o medical diagnostic and treatment equipment		
o advanced telemedicine		
o hygiene and nutrition approaches		
o behavioral health		
o productivity enhancement		
Have you met all key mission constraints/requirements? (4-person crew min, 30 day min Mars surface stay, max 2 year total mission, no more than 5 cargo launches of 130-mT (LEO) payload launch vehicle w/10 meter diameter payload shroud, and one crew launch?		
Have you considered/demonstrated leveraging the SLS?		
Could your system/technologies be available for initial missions by 2045?		
Have you addressed all mission aspects and systems, from launch through return as well as surface systems & activities?		
Do you clearly demonstrate mission benefits (e.g., improving cost, reliability, or safety) of specific human-focused technologies through systems analysis of the entire mission?		
HUMAN LUNAR ACCESS AND INITIAL EXPLORATION	**Y**	**N**
Have you developed an architecture that utilizes two 105t class SLS launch vehicles, the NASA Orion multi-purpose crew vehicle and reusable (partially or fully) low lunar orbit based lander?		
Could your system/technologies be available for initial missions in 2025?		
Have you met the following key mission constraints and requirements?		
o Crew of 4 to the moon, at least 2 to the lunar surface		
o Lunar surface mission of no longer than 28 days		
o Missions to polar regions (sunlit operations only)		
o Pressurized mobility for habitation and exploration		
Have you addressed all aspects and systems, from launch through return, as well as surface systems and activities?		
Do you clearly demonstrate mission benefits (e.g., improving cost, reliability, or safety) of specific human-focused technologies through systems analysis of the entire mission?		
ADVANCED CONCEPT OPTION	**Y**	**N**
Have you demonstrated how the supporting element meets the design constraints of one of the themes?		
Have you demonstrated how the investment in your particular supporting element can be leveraged to be used in the two other architecture scenarios (i.e., themes)?		

APPENDIX D

References

[1] B. Obama, National Space Policy of the United States of America, Office of the President of the United States, Washington, DC: The White House, June 28, 2010.

[2] Review of US Human Spaceflight Plans Committee, N. Augustine, W. Austin, B. Bajmuk, L. Chiao, C. Chyba, E. Crawley, J. Greason, C. Kennel, L. Lyles, et al., Seeking a Human Spaceflight Program Worthy of a Great Nation, National Aeronautics and Space Administration, 2009.

[3] A. Santos, D. Dunham, Near Earth Asteroid Rendezvous Project, aIAA 1993-4089.

[4] M. D. Rayman, T. C. Fraschetti, C. A. Raymond, C. tT. Russell, Preparing for the Dawn Mission to Vesta and Ceres, in: 56th International Astronautical Congress of the International Astronautical Federation, 2005, iAC-05-A3.5.B.01.

[5] J. Kawaguchi, A. Fujiwara, T. Uesugi, Hayabusa (MUSES-C) - Rendezvous and Proximity Operation, in: 56th International Astronautical Congress of the International Astronautical Federation, 2005, iAC-05-A3.5.A.01.

[6] D. R. Adamo, J. D. Giorgini, P. A. Abell, R. R. Landis, Asteroid Destinations Accessible for Human Exploration: A Preliminary Survey in Mid-2009, Journal of Spacecraft and Rockets 47 (2010) 994–1002.

[7] P. Abell, B. Barbee, R. Mink, C. Alberding, D. Adamo, D. Mazanek, L. Johson, D. Yeomans, P. Chodas, A. Chamberlin, L. Benner, B. Drake, V. Friedensen, The Near-Earth Object Human Space Flight Accessible Targets Study (NHATS) List of Near-Earth Asteroids: Identifying Potential Targets for Future Exploration, jSC-CN-25613, GSFC.ABS.6317.2012, JSC-CN-27098 (2012).

[8] R. Landi, D. Korsmeyer, P. Abell, D. Adamo, T. Jones, A Piloted Orion Flight to a Near-Earth Object: A Feasibility Study, in: SpaceOps 2008 Conference, AIAA 2008-3550.

[9] J. Olson, Human Exploration Framework Team Phase I Closeout, National Aeronautics and Space Administration (September 2, 2010).

[10] National Aeronautics and Space Administration, Fy 2013 president's budget request summary, `http://www.nasa.gov/pdf/632697main_NASA_FY13_Budget_Summary-508.pdf` (2013).

[11] E. Morse, J. Fragola, B. Putney, Modeling Launch Vehicle Reliability Growth as Defect Elimination, in: AIAA SPACE 2010 Conference and Exposition, Anaheim, California, American Institute of Aeronautics and Astronautics, 2010-8836.

[12] I. Zeid, Mastering CAD/CAM, higher education edition Edition, McGraw Hill, 2005.

[13] A. Carlisle, G. Dozier, An Off-the-Shelf PSO, in: Proceedings of The Workshop On particle Swarm Optimization, Indianapolis, USA, 2001.

[14] Spectrolab, 29.5% NeXT Triple Junction (XJT) Solar Cell, `http://www.spectrolab.com/DataSheets/cells/PV%20XTJ%20Cell%205-20-10.pdf`, accessed: March 13, 2013.

[15] J. Wertz, W. Larson, Space Mission Analysis and Design, Microcosm, Hawthrone, CA, 1999.

[16] Space Exploration Corp., Falcon 9 launch manifest, accessed: January 1, 2013.
URL `http://www.spacex.com/launch_manifest.php`

[17] United Launch Alliance, Delta launch manifest, accessed: January 1, 2013.
URL `http://www.ulalaunch.com/site/pages/News_Manifest.shtml`

[18] United Launch Alliance, Atlas V Launch Services User's Guide, `http://www.ulalaunch.com/site/pages/Products_AtlasV.shtml`, accessed: January 1, 2013 (2010).

[19] C. Lindsey, Spacex awarded 2 eelv-class mission from usaf, NewSpaceWach, `http://newspacewatch.com/articles/spacex-awarded-2-eelv-class-missions-from-the-usaf.html`, accessed: May 14, 2013 (December 5, 2012).

[20] S. Sachdev, W. Harvey, Canada and the international space station program: Overview and status since iac 2005, in: 57th International Astronautical Congress, Valencia, Spain, International Astronautical Federation, IAC-06-B4.1.3.

[21] J. Fitzsimmons, Possible Uses of a Bigelow-type Commercially Developed Space Facility, in: AIAA 2008-7820, AIAA SPACE 2008 Conference & Exposition.

[22] K. Reiley, M. Burghardt, M. Wood, J. Ingham, M. Lembeck, Preliminary Design of the Boeing Commercial Crew Transportation System, in: AIAA 2012-5106.

[23] Z. Krevor, R. Howard, T. Mosher, K. Scott, Dream Chaser Commercial Crewed Spacecraft Overview, in: AIAA 2011-2245.

[24] D. Kaiser, K. Davidian, J. Foust, I. Christensen, An Industry Structural Analysis and Strategy Insights for the Commercial Crew Transportation Industry, in: AIAA 2011-7288.

[25] B. H. Wilcox, ATHLETE: A Limbed Vehicle for Solar System Exploration, in: IEEE Aerospace Conference, Institute of Electrical and Electronics Engineers, 2012.

[26] R. Binzel, A. Riykin, C. Thomas, P. Vernazza, T. Burbine, F. DeMeo, S. Bus, A. Tokunaga, M. Birlan, Spectral Properties and Composition of Potentially Hazarous Asteroid (99942) Apophis, Icarus 200 (2009) 480–485.

[27] R. Furfaro, D. Cersosimo, D. Wibben, Asteroid Precision Landing via Multiple Sliding Surfaces Guidance Techniques, Journal of Guidance, Control and Dynamics AIAA Early Edition (2013) 1–18.

[28] J. Allton, Catalog of apollo lunar surface geological sampling tools and containers, jSC-23454, LESC-26676, 1989.

[29] W. J. Larson, L. K. Pranke, Human Spaceflight: Mission Analysis and Design, McGraw-Hill, New York, NY.

[30] Bigelow Aerospace, Opportunities and Pricing, accessed May 1, 2013.
URL `http://www.bigelowaerospace.com/opportunity-pricing.php`

[31] S. E. Corp., Nasa selects spacex's falcon 9 booster and dragon spacecraft for cargo resupply services to the international space station (Dec. 2008).
URL `http://www.spacex.com/press.php?page=20081223`

[32] National Aeronautics and Space Administration, Manned Lunar Landing: Operations Analysis and Mode Comparison (Jun. 1962).

[33] S. J. Isakowitz, J. B. Hopkins, J. P. H. Jr., International Reference Guide to Space Launch Systems, 4th Edition, AIAA (American Institute of Aeronautics & Astronautics), Reston, Virginia, 2004.

[34] S. D. Guikema, M. E. Pate-Cornell, Bayesian Analysis of Launch Vehicle Reliability, in: 2003-1175, 41th Aerospace Sciences Meeting and Exhibit, Reno Nevada, 2003.

[35] E. Kyle, Space Launch Report, `http://www.spacelaunchreport.com/`, accessed January 1, 2013 (December 19, 2012).

[36] D. Young, An Innovative Methodology for Allocating Reliability and cost in a Lunar Exploration Architecture, Ph.D. thesis, Georgia Institute of Technology, School of Aerospace Engineering, Atlanta, Georgia (2007).
[37] M. Meyer, Cryogenic propellant storage and transfer technology demonstration for long duration in-space missions, nASA/TM-217642.
[38] M. Gravlee, B. Kutter, M. Wollen, N. Rhys, L. Walls, CRYOTE (Cryogenic Orbital Testbed) Concept, in: AIAA 2009-6440, AIAA SPACE 2009 Conference and Exposition, Pasadena, California, American Institute of Aeronautics and Astronaustics, 2009.
[39] P. O. Wieland, Living together in space: the design and operation of the life support systems on the international space station, nASA/TM 1998-206956.
[40] M. C. Foale, Diagnostic instrumentation aboard iss: just-in-time training for non-physician crewmembers, Aviation, space, and environmental medicine 76.6 (2005) 594–598.
[41] R. Turner, Commercial space tourism and space weather, space Weather 5.8 (2007).
[42] R. Fenton, A ladar-based pose estimation algorithm for determining relative motion of a spacecraft for autonomous rendezvous and docking, proQuest, 2008.
[43] J. Jackson, The interplanetary internet [networked space communications], Spectrum IEEE 42.8 (2005) 30–35.
[44] P. R. Chai, A. W. Wilhite, Cryogenic Thermal Management of Orbital Propellant Depots, in: IAC-11 D1.2.3, 62nd International Astronautical Congress, Cape Town, South Africa, 2011.