Project Alshain: A Lunar Flying Vehicle for Rapid Universal Surface Access

University of Maryland, College Park
ENAE484: Space Systems Design

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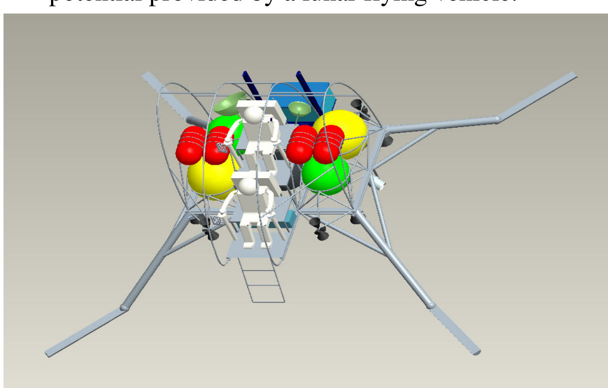
Introduction

Since the Apollo program, the United States has foregone going to the Moon in order to focus on other space applications. However, with the advent of the Constellation Program, NASA plans a triumphant manned return to the moon, and the establishment of a permanent lunar base near the south pole. One goal of the base is to further exploration and research of the lunar surface.

With the installation of a permanent outpost, a transportation infrastructure must be developed in order to efficiently travel, research, and explore the Moon's surface. Since a permanent outpost has never been developed, one can use the Antarctic base infrastructure as an analogue to what means of transportation must be made available in such an uninhabitable, unexplored environment. For example, in Antarctica, scientists have the means to travel short distances between buildings and around the base using snowmobiles, and the ability to conduct longer research missions using closed cabin vehicles. The use of helicopters and aircraft enables unsurpassed range and speed for long distance missions. Similarly, unpressurized rovers could be the snowmobiles of the lunar base, while pressurized rovers are able to conduct missions that are both longer and farther away. However, the means to travel long distances quickly and reach inaccessible areas has yet to be explored in-depth. Thus, a lunar flying vehicle (LFV) has been proposed to accomplish these tasks and supplement the South Pole base transportation infrastructure.

A lunar flying vehicle provides extraordinary potential as a means of transportation on the Moon. Such benefits include access to sites otherwise inaccessible to a lunar rover, including rilles, craters, mountains, and potential lava tubes. To cite a past NASA example, Apollo 15 landed next to Hadley Rille, but was with no means to traverse the slope of the rille, it was left unexplored. An LFV also provides a means of quickly reaching any damaged or broken vehicles, such as a rover, in order to perform crew rescue operations. The unparalleled speed and mobility provided by an LFV make it an ideal choice to supplement lunar exploration.

The concept of a Lunar Flying Vehicle has not been given serious consideration since the late 1960s, and the Apollo program. These projects and others were all given serious consideration, but abandoned as the Apollo program neared its end.[6,7] With the introduction of Constellation, it is time to reevaluate the feasibility and scientific potential provided by a lunar flying vehicle.



Alshain is an LFV designed with the intent to seamlessly integrate with Constellation Architecture. The name Alshain is Arabic for falcon, and also a star located in the same constellation as Altair, the name of the lunar lander being designed for the Constellation program. Alshain makes several assumptions about the proposed Constellation architecture. Alshain utilizes cryogenic liquid oxygen (LOX) and liquid hydrogen (LH2) as its propellant source under the assumption that the Altair lander will be fueled by the same elements and will contain residual propellant that can be used to fuel Alshain. Constellation also seeks to explore the possibility of water ice pockets located on the lunar surface and to develop the infrastructure to extract and separate the water ice into hydrogen and oxygen to be used as propellants. Alshain assumes that when launched to the lunar surface, these in situ production facilities will already exist that the LFV can draw from. Finally it is assumed that the Lunar Relay Satellites (LRS) proposed by Constellation will be functioning to be used for communication and data exchange with the vehicle.[3]

Loads, Structures Mechanisms

Loads

Table 1. Loads Table

Event in Lifecycle	**Type of Load**	**Load**
Launch	-Z	6g
Launch	+/- X, +/-Y	2g
Launch	+Z	2g
Launch-Steady State	+/- X, +/- Y, +/- Z	1.9g --- 1.25g
Landing	-Z	2g
Flight-Main Engine	+Z	2g
RCS Thrusting Vertical	+/-Z	1150 N
RCS Thrusting Horizontal	+/- X, +/-Y	300 N
Kick Loading	+/- X, +/- Y, +/- Z	250 N
Rollover Loading	-Z	1.64 m/s^2

CG Analysis

The CG location was measured relative to a point along the engine's axis of symmetry, 0.1 meters from the bottom of the engine bell. For pre-flight configurations, mass and relative location of each individual component of the craft (including astronauts) is taken into consideration for 18 separate loading scenarios. For post-flight configurations, expendable items on the vehicle (such as propellant), will either be depleted or offloaded at the mission site. The two CG locations of the pre-flight and post-flight configurations bound the envelope within which the center of gravity shifts during flight. The results of the CG analysis are summarized in the tables below.

Table 2. Nominal CG Location for Alshain

	Pre-Flight X (m)	Pre-Flight Y (m)	Pre-Flight Z (m)	Post-Flight X (m)	Post-Flight Y (m)	Post-Flight Z (m)
Nominal Configuration	0.015	3.48E-04	0.437	0.017	5.63E-04	0.368

Table 3. Max CG Shift per dimension

	Shift (m)	Case
Max X-CG Shift (m)	0.164	Crew: One 95th percentile male; no cargo
Max Y-CG Shift (m)	8.79E-04	Crew: None; no cargo
Max Z-CG Shift (m)	0.452	Crew: Two 95th percentile males; no cargo

Support Structure Rationale

As seen in the loads table, the main causes of loading are axial (z-axis), especially in the cases of functioning on the moon. The configuration of the components of the main vehicle is relatively short axially (1.46 m in the z axis), while being relatively wide and deep (y and x directions respectively).This causes large moments to be created by the primarily axial forces, while not allowing for a tall structure to distribute the loading.

In order to counter these large moments, a single support base in the x-y plane and a truss structure were considered. Due to spacing issues with the rocket and crew, a truss system would be impractical. This leads to the use of a single support structure rather than a truss structure. This structure is placed flush with the bottom of the tanks so that the crew can access their seats and the payload bay with ease.

Beam Choice

The choices for beams used in the support structure are determined by an analysis of internal moments and shear forces, with torsion as a secondary concern. Hollow tubular beams and I-beams have been selected for their strengths in taking these three types of forces. The analysis of moment and shear forces concluded that a support structure made of the I-beams would be 80kg less massive than a set of hollow tubular beams. This leads to the choice of I-beams with a 80kg envelope to prevent torsion effects.

I-Beam Analysis

The analysis for I-beams is done by setting the total height and width of the I-beam cross-section and solving for the necessary flange and web thicknesses with a minimum set at 2mm. The web thickness is calculated for failures in shear and vertical Euler buckling and the flange thickness is then calculated for bending forces.

The height of the I-beam is determined by mass, clearance for the rocket nozzle, height in stowed configuration, and machinability. I-beams of 10cm height would be flush with the bottom of the rocket nozzle, while anything larger would increase the stowed height of the vehicle linearly. The results of the trade study show that mass savings drop after 17.5cm height due to the 2mm thickness requirement. This allows for 17.5cm clearance for the rocket nozzle while stowed and is at the point of diminishing returns for mass savings.

Component Attachment System

Due to the choice of support structure placement, an array of small pinned struts is necessary to join each specific component to the support structure. To handle the primarily axial, hollow tubes have been chosen throughout the structure as the truss members. This member choice leads to the analysis of each truss member for solely tensile and compressive forces.

Tubular Member: Axial Loading Analysis

Each tubular member has been considered for four failure types: Tensile strength, compressive strength, Euler buckling, and tubular "shell" buckling. In practice slight machining of 15% wall thickness cause shell buckling failures to occur at 50% of ideal stress values, so the yield stress was doubled for all calculations. The analysis gives a thickness for each beam of 2mm for machinability. Tubes are chosen to minimize mass within a reasonable radius for spacing considerations.

Support Structure Crossbeams

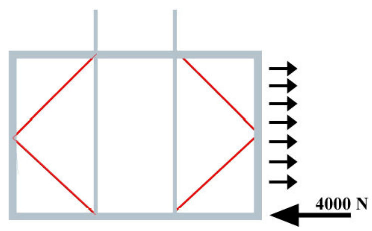


Figure 1. Support Structure

Support structure crossbeams are necessary to maintain stability. The inner area has a natural protection against collapse from the rocket engine, but the outer sections require additional support. The worst case loading scenario for collapse of the support structure is $2 m/s^2$ lateral force during a two leg landing, corresponding to a shear force of 4,000 N. This distributes to the symmetric crossbeams, leading to a compressive force of 2830 N. Running a tube analysis for compression over a range of radii leads to an ideal beam size of 1.5cm radius, 2mm thickness and 0.75kg mass per member.

Tank Support Structure

The fuel support structure is designed to connect the LOX and LH2 tanks to support structure below. The stowed (without fuel) load scenario and take-off and landing scenarios (with fuel) were considered. Under the worst case scenario the LOX tank creates an axial force of 7630 N and a lateral force of 763 N, while the LH2 tank creates a 1270 N axial force and a 127 N lateral force. Each numbered point in Figure 3 refers to a pair of supports placed at 45 degrees. The pressurant tank worst case scenario is Earth launch, involving two supports per tank. The pressurant tank supports hold 3kN axial and 1kN lateral force per pair. The rearward pressurant tank supports rest on the (6) and (7) fuel tank support sets.

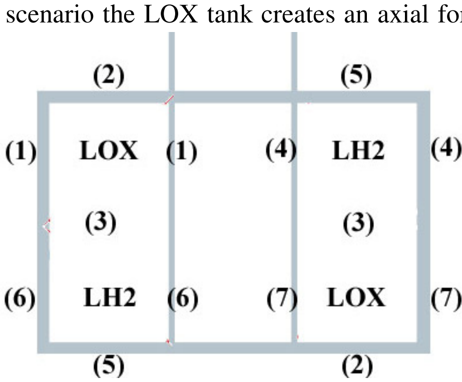


Figure 3. Fuel Tank Support Structure

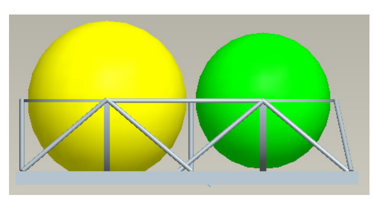
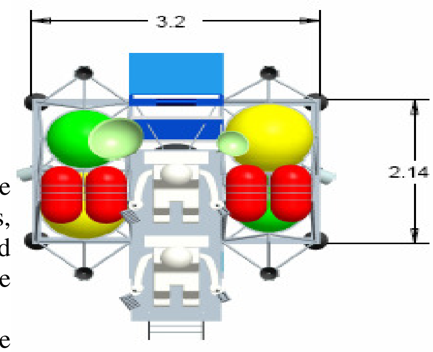


Figure 2. Fuel Tank Support Structure Side View



Rocket Support Truss

The rocket support truss serves a dual purpose in that it supports the rocket, but also braces the central support structure against collapsing forces, with attachment points at corners to minimize torsion. The 6G axial stowed and 2G lateral loads (compressive) and the take-off case of 40kN (tensile) are the worst cases. The beams are oriented at θ=53.3 from the z axis.

This leads to an applied tensile force of 12.5 kN and a compressive force of 3.76 kN. The tubular member analysis concluded that the determining failure was due to the compressive force.

Table 4. Margin of Safety

Tube Inventory	**Piece Designation**	**Applied Load (N)**	**Breaking Load (N)**	**MOS %**
Engine	**Support Tubes**	3760	5950	13.2
Fuel	**(1) and (2)**	1490	2460	18.3
	(3)	1730	2460	1.4
	(4) and (5)	250	480	37.5
	(6)	2720	5180	36.0
	(7)	2830	5180	31.1
Pressurant	**Rear**	2990	4430	5.9
	Front	2480	3570	3.0
Support Structure	**Crossbeams**	2830	4840	22.2
Landing Gear	**Support Tubes**	106,000	151,500	1.9
I-beam	**Piece Designation**	**Applied Force**	**Breaking Force**	**MOS %**
Lengthwise	**Shear Force (N)**	12,500	72,450	
	Moment Force (N-m)	30,000	43,940	4.6
Widthwise	**Shear Force (N)**	1,875	72,450	
	Moment Force (N-m)	18,300	26,600	3.9
Crew Support	**Shear Force (N)**	4,670	33,120	
	Moment Force (N-m)	3,180	5,150	15.7

Fuel Tank Cradles

In order to secure the LOX and LH2 tanks within the structure, semicircular cradles with rectangular cross sections are used. A cradle cross section thickness (measured radially from tank center) was chosen and the cross section width (completing the rectangular cross section) of the various cradles was varied. The LOX cradles are 2.6kg each and the LH2 cradles are 0.6kg each.

Crew Platform

For the crew platform, a honeycomb will be used to support astronauts. The worst case loading of 2 g's was used, which corresponds to 3400N from the astronauts. Aluminum Flex-Core honeycomb was chosen. The specific designation is CR-PAA-5052/F40-.0013"-2.1", which has a phosphoric acid anodized coating, 5052 aluminum alloy and has density of 2.1lb/ft^3. Each honeycomb cell will have dimensions of .75" width, .75" length, height of .25", and an individual wall thickness of .0013". With this dimension, this honeycomb can stand up to 1.4GPa. The total mass of crew platform is 1.44 lb, which yields 0.66kg.

Roll Cage

The roll cage is designed to shield Alshain's crew and sensitive components from rollover. It is dimensioned to provide a 30-centimeter clearance at all points around the crew and pressure tanks in order to protect from obstacles 30 centimeters or less in height. The design includes 4 elliptical arches, each 2.4m tall, connected by a total of 7 crossbars (3 on each side of the tank compartment, 1 bracing between the crew compartment). The roll cage can withstand up to $6g_{moon}$ forces with a safety factor of two. The maximum specifications of the roll cage are listed below.

Table 5. Roll Cage Margin of Safety

Member	Bending Stress (MPa)	Compressive Stress (MPa)	Margin of Safety	Mass (kg)
Crew Cage	1.04E-03	24.8	5.28	12.26
Tank Cage	4.14E-03	68.9	1.25	3.92
Tank-Crew Crossbar	N/A	60.4	1.56	0.85
Crew-Crew Crossbar	N/A	60.4	1.56	0.89

Landing Gear

Being able to absorb landing shock is critical to mission success. In the case of Alshain, the vehicle must be able to absorb a 3 m/s vertical velocity and a 1 m/s horizontal velocity while landing on a 15 degree slope and negotiating a 30 cm high obstacle. The Alshain must be able to land repeatedly so springs are required. The worst case scenario is landing on a 15 degree slope with the back legs propped on 30 cm objects. Due to this requirement, the landing accelerations were split into two components: horizontal, handles by a linear spring in the footpads of each leg; and vertical, handled by separate linear springs running along the length of the landing gear. The analysis shows that the landing gear should be comprised of four legs. Optimizing for minimum mass gives legs that are each 2.3 meters from the base to the tip, have a vertical stroke of .82 meters (using torsion springs), an uncompressed height of 1.33 meters, and a horizontal spring contained in a separate footpad that is 1.64 meters long.

Thermal Shield

To shield the landing gear from the engine plume, the landing gear will be covered with thermal shielding. The chosen thermal shield is a Flexible Insulation Blanket (FIB). The FIB has low density and has the ability to withstand high temperatures. This thermal shield can stand up to 1700K, is made out of ceramic matrix composite, and is easily machinable. When covering the landing gear legs with this thermal shield only half of it will be covered because the engine plume will only contact the inner half of the leg. The dimensions and the mass of FIB are calculated below:

Table 6. Landing Gear Thermal Shield

Number of Legs	**Radius (m)**	**Length (m)**	**Thickness (m)**	**Area (m^2)**	**Mass (kg)**	**Total Mass (kg)**
4	0.065	2.9	2.54E-04	0.59	0.022	0.087

Crew Systems

Contingency Radiation Protection

Contingency radiation protection was found to be unnecessary based on a 0.05% probability of a dangerous Solar Particle Event (SPE) occurring in a 24 hour period and a mission reliability of 99.2%. [5] With a project lifetime of 250 missions, the likelihood of both a mission failure and dangerous SPE event occurring simultaneously is less than 1 in 1000.

Crew

Design considerations included accommodations for crew members ranging from 5th percentile American females through 95th percentile American males. The range of suited crewmember masses considered was 120 kg – 170 kg. The range of suited crewmember heights considered was 1.7 m – 1.9 m. [4]

Seating

The seating configuration was based on rover seats which are designed to accommodate EVA suited astronauts.

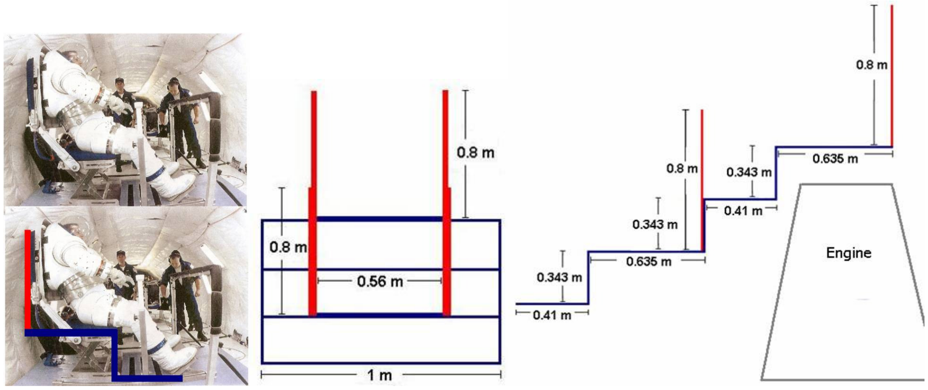


Figure 4. Crew Seating[1]

Seat dimensions were based on the results of a partial gravity rover seating design study. [1]

Restraints

The red bars shown in the previous figures represent Personal Life Support System (PLSS) supports and restraints. By restraining the PLSS, the hard upper torso of the Constellation spacesuit is also restrained from motion. The crew's feet are restrained from kicking up during flight by boot restraints located at the back of the heel.

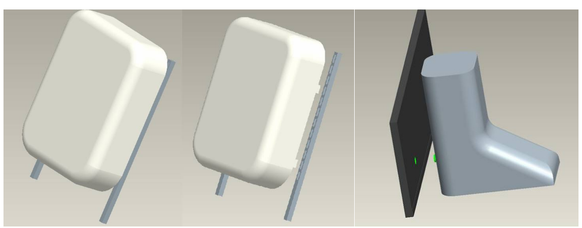


Figure 5. PLSS and Boot Restraints

Sightlines

The nominal pilot of the Alshain is the forward crewmember. The limiting factor of the sightlines of the forward crewmember is their own lower body (limited to 45° downward). The aft crewmember is also supplied with a set of control towers and is able to pilot the craft in a contingency situation. However, the sightlines of the aft crewmember are further obstructed by the forward crewmember (limited to 30° downward).

Hardware Testing

Hardware testing was conducted to confirm the feasibility of ingress/egress as well as an incapacitated astronaut rescue. Suited ingress and egress was successful, aided by handholds provided by the roll-cage structure. Incapacitated astronaut rescue testing is ongoing. Hardware testing images are attached in Appendix B.

Elevator

The hardware elevator consists of a 1 by 0.6 m wooden elevator platform attached to two 1.7 m aluminum guide tracks. The elevator platform is raised and lowered using a high torque AC motor which winds a lifting rope.

The main advantage of an elevator is its small footprint. With an elevator, the elevator platform acts as the vehicle's payload bay. Once the payload is loaded onto the elevator, the platform is raised to its flight position and the payload remains there. The elevator also has the advantage of being a symmetrical system. When the elevator is mounted on the rear of the vehicle it maintains its lateral symmetry, simplifying the center of gravity calculations and minimizing use of the

Figure 6. Hardware Payload Elevator

reaction control system.

Lighting

The lighting configuration on the lunar flying vehicle must ensure sufficient illumination to allow safe flight in daylight and night conditions. In all crew control areas, the lighting must be able to dim in order to accommodate different contrast conditions. The lighting must also be able to properly function in the unpressurized, temperature-varying lunar environment. For this reason, halogen lamps were chosen over LED lamps, as LED lamps would require an extra pressurized housing in order to operate in lunar conditions.

Debris protection

The engine plume of the Alshain has enough energy to eject lunar particles around the vehicle during takeoff and landing at high speeds. These particles have the potential of redirecting back towards the Alshain, and hence the astronauts. To save mass and space on the vehicle, a non-structural debris shield configuration was chosen. The body of a crewmember will be protected by an extra Thermal and Micrometeoroid Garment (TMG) debris shield, worn like a sleeved blanket and clipped to the metal ring that connects the space suit helmet and Hard Upper Torso (HUT). The head of a crewmember will be protected by a polycarbonate shield that snaps to the top of the PLSS and clips to the metal ring that connects the space suit helmet to the HUT.

Avionics

Avionics Overview and C&DH

Alshain's avionics system controls most of the onboard vehicle's systems. Its functions include automatic determination of the vehicle's status; operational readiness; performance monitoring; digital data processing; communications; guidance, navigation, and control. Avionic systems are designed to withstand multiple failures through redundant hardware and software. These are managed by a complex of four computers to meet the two-fault tolerance level one requirement.

In aid to the onboard avionics, Alshain will make use of Lunar Relay Satellites (LRS) intended as part of the Constellation program. These satellites are capable of one-and-two way ranging and are fully capable of relaying both S and Ka band communications. These satellites will primarily be used for command and telemetry between the vehicle and the lunar base. If Alshain is at a location where it can not make direct to earth communications link to the Deep Space Network (DSN) antennas on Earth, LRS' will be used as a medium to create the link.

Alshain is required to communicate directly to the lunar base. Lunar Communications Terminals will be established at the base for this purpose. These terminals will be planted very close to the lunar base and are capable of transmitting both S and Ka band along with WLAN. They are capable of one way ranging as an additional navigational aid, which Alshain may require for an emergency return to base in the event of a significant loss of onboard navigational systems.

The Command and Data Handling (C&DH) system distributes commands, records telemetry, and keeps various components' status updated in real-time. The C&DH is comprised of an enclosure, a backplane, four single board computers, S-band and Ka-band communications interface boards, data storage boards, a housekeeping and digital input/output board, and analog data acquisition boards. All electrical connections between these components are made via the backplane for internal power distribution and PCI bus data transfers. The interfaces between the C&DH and other avionics components are connected through a SpaceWire network.

Guidance

The vehicle will follow a modified ballistic trajectory, transitioning into a propulsive glide on the final approach to the destination to allow the crew to visually inspect the landing site and redesignate the target as necessary. Control levels are provided for three different levels of human involvement—autonomous, direct, and teleoperation. Under autonomous control, the vehicle's onboard computers will manage all aspects of flight without the need for external intervention. Under direct control, automatic control loops will maintain pilot-specified rates, both in translation and rotation. Teleoperation is similar to the autonomous mode, with the exception that the lidar scan will be transmitted to a remotely located pilot and human judgment will be used to select the landing site.

Navigation

Once a position and attitude fix is determined from external references prior to launch, the vehicle will be capable of reaching the destination under inertial navigation alone (with the exception that ranging to the ground may be necessary at the very end to properly null velocities for landing). The system was designed as such because it is not currently known whether navigational updates will be reliably available in flight.

There are very few ways to quickly determine one's position relative to an unseen reference (e.g., the origin of the Earth-Centered Inertial frame). Of the options which exist for determining an initial attitude fix, star trackers were chosen because the stars are available as a reference from any location on the surface of the moon—as opposed to the sun or the earth which will not necessarily be visible. Star trackers are capable of providing full attitude information about yaw, pitch, and roll. Two units will be mounted pointing up from the top of the vehicle at an angle of 45 degrees, and separated by 90 degrees. To help mitigate obstruction of the optical elements due to dust accumulation, covers will be placed over the baffles when not in use.

Error Budget

An estimate was made of the total expected final error in touchdown site due to the various sources of navigational error, both in the initial fix and in the inertial propagation of that fix. A redundant system of four inertial measurement units will ensure that pure inertial navigation is possible even in the event of two IMU failures. The contributions of each error source to the final position knowledge were combined to produce an overall estimate. For the purposes of this analysis, the low and high frequency uncertainty sources were treated separately, with sums taken for each category which were combined in a root-sum-square. At maximum range, this system is capable of providing 38 meters accuracy, well within the desired vehicle performance.

Control

The initial launch and acceleration phases of the flight will follow pre-programmed guidance which specifies acceleration, velocity, attitude and attitude rates as a function of time. Once the acceleration phase is complete, control will change to a target-centric algorithm using a propagated trajectory based on the navigation data. The target during this phase is a point in space (with some tolerance) at which the deceleration phase begins. During deceleration, the radar altimeter will be incorporated and the thrust vector will be set so that the vehicle will have zero vertical velocity and a predetermined in-track velocity at some predetermined altitude. Thus, the vehicle will come out of the ballistic trajectory and into a propulsive glide at a specified altitude.

Status Monitoring and Fault Tolerance

The vehicle shall monitor all critical parameters to enable identification and handling of faults. The two primary vehicle systems requiring status monitoring are the power and propulsion systems. Propellant levels will be monitored to allow for estimation of remaining delta-v available. A radio frequency gauging technique is currently in development that will work at cryogenic temperatures. The pressure before and after all valves and regulators in the propellant feed system will also be monitoring to enable diagnosis of faults. The power system will require monitoring of battery and fuel cell voltages, along with the temperatures and pressures of the oxygen and hydrogen entering the fuel cell system. Data from the suits consisting of heart rate and other physiological parameters will also be relayed to mission control.

The vehicle has been designed to provide two-fault tolerance. It will carry four flight computers, operating in parallel, voting in the event of a discrepancy. Except in the unlikely event of a two-two split, this will allow for isolation of up to two computer faults. Redundant wiring will ensure that faults in the command and data handling system do not interfere with use of critical navigational instruments. Navigational instruments were chosen such that the loss of any one device would not cause loss of mission, and the loss of any two devices would still allow a safe return to base. Via ranging to the Lunar Communication Terminals, the vehicle can return to base even in the event of a significant loss of navigational functionality.

Communications

The Constellation architecture as planned by NASA will use Ka-band and S-band for the primary communications links both among surface nodes and between the lunar surface and Earth. For the purposes of this project, it is assumed that the Deep Space Network 34 m BWG antennas would be available for a direct-to-Earth communications link with Alshain in both frequency bands in addition to the Lunar Relay Satellites. Stationary surface nodes such as lunar communications terminals (LCTs) may also serve as relays, hubs, and navigational aids that use radiometrics to aid landings in case other navigational hardware, such as LIDAR, fails. The 26 GHz Ka-band downlink will be capable of at least 100 mbps and will be used for high-bandwidth mission data such as video or scientific data in addition to LIDAR scans in autonomous and teleoperation modes.

The primary high gain antenna (HGA) used to transmit and receive this data will be a 0.66 m diameter parabolic dish mounted on top of the vehicle and will be driven by a traveling wave tube amplifier capable of over 40 W output power. There will also be a backup 0.3 m dish capable of 30 mbps that will enable mission continuation of the mission, albeit with degraded performance, should the primary unit fail. The 2.2 GHz S-band omnidirectional downlink will be capable of at least 160 kbps. Wireless local area network (WLAN) will also be used for compatibility with the envisioned lunar surface architecture.

Power, Propulsion, and Thermal

Main Engine System

Design of the Main Engine System (MES) on the Alshain was performed using a combination of thermodynamic relations for an ideal rocket and historical examples of LOX/LH2 engines. Because existing LOX/LH2 engines are much too large for use with a small vehicle, we had to estimate the characteristics of an engine built specifically for this application. The resulting Main Engine System consists of a single 40 kN engine, 100 cm tall by 80 cm in diameter, with an I_{sp} of 400 seconds, expansion ratio of 45:1, a chamber pressure of 2.0 MPa, and weighs 96 kg.

Determining the amount of thrust the system would be capable of was a function of crew safety, minimizing waste of fuel due to gravity drag, and minimizing engine mass. In order to prevent injury to the crew of the Alshain, a maximum acceleration of 2 g's (19.6 m/s^2) was set. Fully fueled at approximately 2500 kg, the Alshain would achieve 2 g's with approximately 49 kN of thrust, which set the upper limit on thrust capability. Gravity drag – the term given to the reduction in ΔV capability of an engine due to the presence of a gravity field – is minimized by increasing thrust to reduce burn time. The amount of fuel required to achieve a given ΔV is dictated by the following relationship:

$$\Delta V = -V_e \ln\left(\frac{m_f}{m_i}\right) - \frac{gV_e}{T}\left(m_i - m_f\right)$$

Where V_e is exit velocity, g is the moon's gravitational acceleration, T is thrust, and m_f and m_i are the final and initial masses, respectively. Combining this with a mass estimating relationship of 2.4 kg per kN of thrust (determined by a linear regression of historical engines), total system mass is minimized with a thrust of 40 kN.

A single engine system was chosen on the basis that multiple engine systems increase the likelihood of an engine failure event. A single 40 kN engine was then analyzed using thermodynamic relations for an ideal nozzle to determine its size and performance characteristics. An expansion ratio of 45:1, which yields an I_{sp} of 400 seconds, was chosen based on a point of diminishing returns from having larger nozzles. The chamber pressure of 2.0 MPa was chosen primarily to minimize the mass of the propellant and pressurant tanks, but also out of nozzle size concerns.

Propulsion Analysis and Tank System

The Alshain has specific ΔV requirements for the max mission distance. Each ballistic hop will take 700 m/s of ΔV and there is an additional glide ΔV of 200 m/s for picking the landing site. This gives a total ΔV of 1600 m/s. In addition, there must be extra fuel added for the PEM fuel cells, the RCS system, and to account for gravity drag (a non-impulsive burn penalty). The ΔV requirements must met using LOX and LH2 as propellants

Table 7. Fuel Masses

Fuel Uses	Mass [kg]
Flight	700
RCS	100
Fuel Cells	3
Gravity Drag	137
Total	**940**

From the mass budget, the approximate inert mass of the vehicle is 1100 kg with a 30% margin. In addition to this inert mass, the Alshian must also be capable of carrying two astronauts plus additional payload. This additional payload must be equal to at least the weight of an additional astronaut. This gives a total payload requirement of 500 kg. The table to the right shows the fuel breakdown to meet all these requirements.

For the tank system, there are several requirements: meet all NASA safety requirements (safety factor of three on high pressure tanks), minimize the total mass, and lower the vehicle volume as much as possible. The graph below shows that spherical tanks are preferable to cylindrical from a mass perspective, hence spherical is the chosen shape for the propellant tanks. For number of pressure tanks, the bottom right graph shows that around 4 pressure tanks. Alshain must fit on the deck of the Altair lander, which to the current knowledge of the design team is 6 by 8 meters.

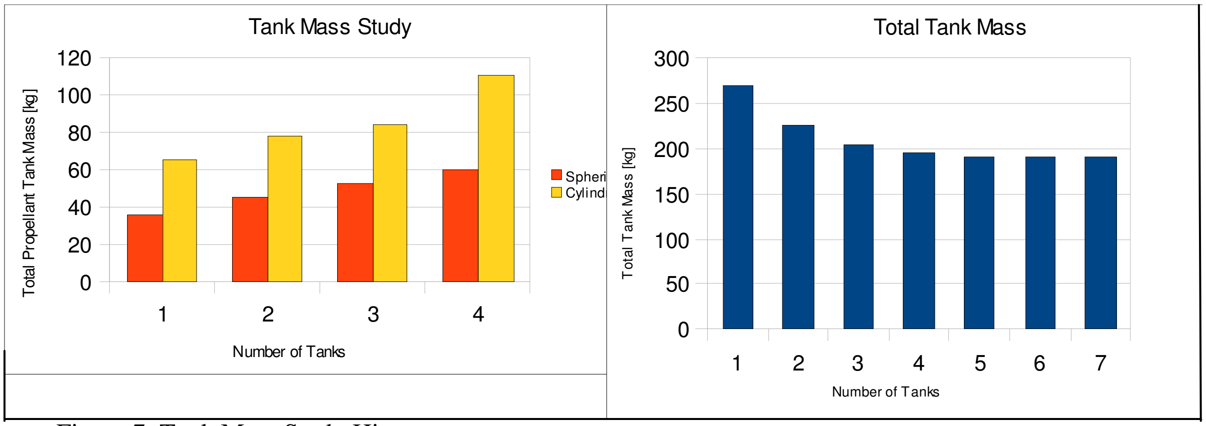


Figure 7. Tank Mass Study Histograms

When the system is compiled, the final masses, dimensions and pressures for each aspect of the tank system are as follows:

Table 8. Tank System Statistics

	LOX	LH2	He
Number	2	2	4
Mass of Tank (each) [kg]	9.4	13	31.5
Mass of Propellant/Pressurant (each) [kg]	402	67	10.5
Pressure [Mpa]	2.4	2.4	8.5
Inner Length [m]	NA	NA	0.4
Radius [m]	0.5	0.43	0.45

Reaction Control System

The reaction control system is required to maintain 6 degree of freedom control. It is comprised of 20 thrusters of two different thrusts and 8 mounting locations. These locations were chosen to ensure proper control as well as to protect the astronauts and vehicle from plume impingement from the thrusters. These thrusters maintain control over the worst case scenario center of gravity shifts. Moreover, the RCS system can be used to safely land the vehicle in the event of a main engine failure. Finally, all systems are designed to have two-fault failure tolerance as per NASA requirements.

To maintain the control of the RCS system to all design parameters, the thrust vector of the main engine must always remain under the center of gravity. The maximum CG shift in the x direction is 0.16m and in the y direction is 0.01m. This equates to a required 6400 Nm pitching torque and a 35 Nm rolling torque.

The factors that affected the thrust requirements were acceleration in all directions, propellant mass flow, size of the thrusters, and mass of the system. Six LOX/LH2 1150N thrusters with a 120 sec burn time use the same amount of propellant as the main 40,000N thruster with a 20 sec burn time. At 120 seconds of burn time, the mass of the thrusters versus burn time trend reaches a point of diminishing return, so this was the burn time that was chosen. To maintain attitude control and traversing control in the x and y directions, eight 450N LOX/LH2 thrusters were placed on pods that were boomed out using a triangular space truss structure. The chamber pressure of these thrusters was increased to the maximum system level of 2 MPa to decrease nozzle size and plume expansion to protect astronauts. Below is a summary of the thrusters, RCS placement, and control.

Table 9. Thruster Specifications

Thrust	Mass	Isp	Ve	Mix Ratio	mdot	Po	Ae/At	Length	Diameter
[N]	[kg]	[sec]	[m/s]	[-]	[kg/s]	[Pa]	[-]	[m]	[m]
450	1.08	415	4070	6	0.11	2.00E+06	115	0.067	0.053
1150	2.75	415	4070	6	0.28	2.00E+06	115	0.27	0.21

Table 10. Summary of RCS Thrust and Moment Control

	X Thrust	Y Thrust	Z Thrust	Pitch Moment	Roll Moment	Yaw Moment
	[N]	[N]	[N]	[N-m]	[N-m]	[N-m]
+	900	900	4600	13710	5640	900
-	900	900	9200	13710	5640	900

Thermal

The thermal control system of the Alshain lunar flying vehicle will have the responsibility of controlling and regulating the temperature of certain subsystems of the vehicle for the worst case temperature scenarios. These subsystems include the seating structure of the astronauts, the avionics box holding the electronics, the fuel cells, and the tanks storing the cryogenic fuels. These heat fluxes include internal power consumed by the electronics and fuel cells, the heat emitted from the astronauts, direct solar radiation from the sun, solar albedo which is solar radiation reflected off of the lunar surface, and also planetary radiation which is the radiation being emitted by the moon itself.

In order to keep the astronaut spacesuits safe from thermal damage, the seating structure of the vehicle must be maintained at a temperature below 320 K. For this matter, the Aeroglaze A276 white paint was chosen. Using this paint, in a worst-case hot scenario, the equilibrium temperature of the seating structure comes down to a safe temperature of 311 K.

Table 11. Avionics Box Electronics

Mass Data Storage	65 W
FPGA/DSP	75 W
IMU	45 W
WLAN	50 W
Flight Computers	100 W
S/Ka Band Transceivers	125 W
Interface Box	75 W
Total with 30% Margin	**695 W**

Table 11 lists the electronics inside the avionics box along with their amount of power consumption. The power consumption of these electronics generates vast amounts of heat inside the avionics box. This heat must be dissipated in order to maintain the electronics at a safe temperature.

Flexible optical solar reflectors were chosen to be used as the radiation medium on top of the avionics box. Using a surface area of 2.3 m^2 gives a safe equilibrium temperature of 306 K. During the worst case cold scenario there will be only 195 W of internal power consumption during 24 hour emergency situations. This leads to an equilibrium temperature inside the avionics box of 204 K. The chosen design for this situation is a set of thermal louvers that will be placed on top of the radiation surface area to increase the temperature of the avionics box to a safe range.

Finally, the cryogenic tanks, have to be thermally insulated again worst-case hot scenarios. To accomplish this, Aluminized Kapton multi-layer insulation with an effective emissivity of 0.002 was chosen for insulation.With one layer, the total boil-off from each tank during worst-case hot scenario duration of 32 hours (8 hour mission and 24 hour emergency) will be 0.04 kg for liquid hydrogen and 0.05 kg for liquid oxygen.

Power

The Alshain has two fuel cells and two sets of batteries ensuring the delivery of necessary power even in the worst-case scenario. To better analyze the power requirements, three possible scenarios were created: in-flight, landed at mission site, 24-hour contingency. Table 12 shows the calculations and lists the power draw, duration, and total energy for each scenario.

Table 12. Power System Characteristics

Equipement	**In-Flight (W)**	**Landed (W)**	**Contingency (W)**
Computation & Communication	660	465	170
Propulsion	175 (pulse)	--	--
Control Panels & Lighting	370	90	40
Life Support	--	--	250
Total Power	1030 (1200 pulse)	555	460
With 30% Margin	**1340(1560 pulse)**	**720**	**600**
Duration	6 min.	8 hours	24 hours
Total Energy	**156 (Wh)**	**5760 (Wh)**	**14400 (Wh)**

While in-flight, Alshain demands high power for a short duration of time. Lithium-ion phosphate batteries ($LiFePO_4$) are a type of Li-ion batteries that have high power densities. The battery mass required to power Alshain for a round trip of 12 minutes is 3 kg. When landed, the power system needs to provide 700 Watts to Alshain for 8 hours. During this time, one fuel cell operates, while the other remains on stand-by in case the first fails. The fuel cell measures 20 cm in length, 10 cm in height and width, and weighs 3 kg. An 8-hour mission requires 0.29 kg of H_2, 2.84 kg of O_2, and creates 2.55 kg of water, which along with the extra oxygen, is stored in the water tank. In the unlikely event that Alshain suffers an accident and cannot return to base, preparations have been made for a 24-hour contingency to allow for crew survival. In this contingency plan, the fuel cells can provide power if there is 9.4 kg of propellant left to provide 14 kWh. If the fuel cannot be accessed, Alshain has 24 kg of CFx batteries to compenste.

The four power sources connect to a power management and distribution unit (PMAD). The PMAD has control of the fuel cell operation and uses back-boost choppers to ensure that the electronics receive the correct voltage. Furthermore, it acts as an uninterruptible power supply by automatically switching to a working power source in case one fails. To summarize, Alshain's power system has two sets of batteries and two 700-Watt fuel cells. Table 13 lists the mass estimation for each component.

Table 13. Power System Component Mass

component:	$LiFePO_4$	CFx	Fuel Cells	F.C. Piping	Wiring	PMAD	Total
mass (kg):	3	24	6	4	5	18	60

Mass Budget

The mass budget was maintained with a 30% margin.

Table 14. Mass Budget

Component	Estimate		Margin		Budgeted	
LOX Tanks	19	kg	5.7	kg	24.7	kg
LH2 Tanks	26	kg	7.8	kg	33.8	kg
Pressure Tanks	168	kg	50.4	kg	218.4	kg
Rockets/RCS	185	kg	55.5	kg	240.5	kg
Power/Wiring/Thermal	60	kg	18	kg	78	kg
Crew Interfaces/Support	54	kg	16.2	kg	70.2	kg
Lighting/Crew Shielding	47	kg	14.1	kg	61.1	kg
Landing Gear	87	kg	26.1	kg	113.1	kg
Structure	101	kg	30.3	kg	131.3	kg
Avionics	122	kg	32.7	kg	154.7	kg
Reserve			256.8	kg		
Total Inert Mass	869	kg			1125.8	kg

Mission Planning and Analysis

Egress from Altair Lander

Alshain is being transported to the moon on an Altair cargo mission. It is designed to be transported aboard the six-meter diameter cargo platform of Altair after the full construction of the lunar outpost (estimated 2020). The tools that will be used from the surface architecture include the Tri-ATHLETE, the power supply unit (PSU), the lunar surface manipulator system (LSMS), and the Crew Mobility Chassis (CMC). [2] The Three-legged All-Terrain Hex-Legged Extraterrestrial Explorer, Tri-ATHLETE, is a unit that can be operated either autonomously or with minimal crew involvement to unload payloads, up to 14.5 tons, from the cargo bay of the Altair vehicle. It either relies on its internal power supply, which is a 6.5 KWh Li-ion battery, or the PSU that enables a 5 km range. The Tri-ATHLETE comes fully equipped and stowed on each cargo mission to unload the payload. The LSMS allows the Alshain to be removed from the Tri-ATHELETE and placed wherever desired. It has the ability to lift up to 6 tons. The CMC can tow up to 3,000 pounds and can operate either autonomously or manually. [2]

Mission Plan for Egress of Alshain

In order to unload Alshain from Altair several tasks have to be undertaken. The first task will be completed by the Tri-ATHLETE unit integrated with a PSU. The legs of the Tri-ATHLETE will deploy to move the Alshain off the Altair. Once the Tri-ATHLETE has cleared the Lander, the Lunar Surface Manipulator System, mounted to the Crew Mobility Chassis, will connect to Alshain's roll cage and lift it off of the Tri-ATHLETE. It will then move Alshain to the launch pad where the landing gear will be re-attached for flight. Reattaching the landing gear will require a crew EVA to fasten them into place. The LSMS and Tri-ATHLETE will then return to the lunar base.

Payload Bay Sizing

The Alshain payload bay has a contingency requirement to support an incapacitated astronaut in emergency situations. For the payload bay to be compatible with an upright-seated astronaut, the platform must support payload weights of 170 kilograms and payload platform area of 0.86x1.0m with a clearance height of 1.49m (volume of $1.28m^3$).

Using these payload bay parameters as a baseline, it was essential to analyze whether these parameters would allow the Alshain payload bay to be adequately compatible with common scientific payloads. Thus, a database of 104 payloads was constructed from NASA documents consisting of past Apollo science payloads and future science payloads slated for use on the Moon and Mars. By analyzing scientific paylods, the point of diminishing returns would dictate a 40kg payload bay capability. This is well within the range of the requirements of supporting a downed astronaut. The same can be seen with the volume of the payload bay versus percentage of compatible payloads, where a $0.28m^3$ meter payload bay is sufficient.

Locking Mechanism for Payload Bay

In order to safely secure payloads, an adaptive method was created which allowed for payloads of different shapes and sizes to be stowed and removed by astronauts while on EVA. The payload bay platform will be made out of an aluminum isogrid. The isogrid will contain a series of equilateral triangles where mushroom locking mechanisms will fit to secure the payloads. Payloads will not only be placed in a predetermined location to balance the payload bay center of gravity, but their fixed location will prevent shifts in the C.G. The isogrid material has a high strength to weight ratio. The largest payload is that of a downed astronaut. For this scenario, a payload bay attachment is fitted into the isogrid floor. The attachment contains a seating area equipped with a PLSS locking attachment and foot constraints to keep the astronaut within the 0.86x1.0m platform area and a clearance of 1.44 m for a 95th percentile United States male. The isogrid has been designed to support the 170kg payload mass of the downed astronaut.

Craters

Craters are important locations to visit for both scientific and logistical reasons. Since craters are formed by impacts from extra lunar bodies, such as meteorites and comets, the crater floors often contain deposits of materials that would not be normally found in the regolith on the surface of the moon. Of particular interest are deposits of hydrogen, which have been detected in the bottoms of certain craters and may indicate the presence of water.

Additionally, crater floors that are protected from exposure to direct sunlight, due to crater depth and location, will contain larger quantities of intact volatile compounds than otherwise. These include water molecules, which would evaporate and be lost if exposed to sunlight. The craters near the lunar base site, because of their proximity to the lunar south pole, remain in nearly perpetual darkness.

Refueling and Return to Base

Plans for refueling the Alshain assume that in situ propellants on the moon are made accessible by a propellant processing station provided by the Constellation Lunar Surface Architecture. This station will have both the capability of processing residual propellants from the Altair Lunar Lander as well as the in situ propellants on or within the lunar surface and all the necessary equipment to transport cryogenic propellants to and re-supply Alshain.

A 10m x 10m landing pad will be used to enable the Alshain to land as close as possible to a lunar base while preventing hazardous ejecta upon landing. After considering different materials for the landing surface, the use of a fire blanket (commonly used by firefighters) was found to be a simple yet viable solution. The Insulflex Pyroblanket (17oz) has the ability to remain intact under temperatures up to 1500 K and is made of silicone rubber that has a mass of 60 kilograms for a 100 square meter area.

Costing Analysis

The Alshain Lunar Flying Vehicle was designed to operate as support to the Constellation program. The Constellation program is planned for a return to the moon by 2020 and therefore, the Alshain LFV will be designed to be available for launch in 2020. In order to estimate the expected production and development costs of the Alshain LFV, several assumptions were made. The first assumption is that the Alshain LFV will be capable of being launched on the initial flight of the Ares V in 2020. The second assumption states that a learning curve of 85% was used when calculating recurring production costs. The third assumption is that two Alshain Lunar Flying Vehicles in case of rescue operations on the lunar surface. All of these assumptions were entered in the two NASA Cost Models used to calculate the cost of the Alshain program.

As stated, two NASA Cost Models were used in determining the production and development costs of two Alshain lunar flying vehicles. The first was the NASA Spacecraft/Vehicle Level Cost Model. The second was the NASA Advanced Missions Cost Model. Each model requires input from the user in order to calculate the costs. There are two important inputs in both cost models. The first is the mission type. Neither of these two models currently have a lunar flying vehicle as a selection for the mission type. Therefore, the final production and development costs of the Alshain program are a rough estimate based on the output of each NASA Cost Model. The second is the dry weight. The dry weight is the mass of the vehicle without fuel, consumables, science and research packages, and astronauts.

The two NASA Cost Models output the cost estimates in 2004 dollars. In order to improve the cost estimates, an inflation calculator was used. The inflation calculator accounted for inflation rates and output the cost estimates in 2008 dollars. The inflation calculator is found on the *United States Bureau of Labor Statistics* government website. A preliminary estimate of development and production costs can be made from analyzing the two NASA Cost Models. The preliminary estimate along with costs from each model is shown in Table 25.

Table 15: Preliminary Estimate

Millions FY2008 US$	SVLC Model	AMC Model	Estimate
Development	1,104	745	~900
Production	128	537	~300
Total	1,232	1,282	>1,300

Outreach

As part of the Alshain project, there was a concentrated effort to reach out to the youth of the community, and engage them in an educational and interesting way. The two goals for the outreach program included 100% team participation and 150+ hours of total outreach. Both goals were met or surpassed with a total of 198 hours of outreach from 15 events. At every step along the way, the team was able to discuss our work, the work of NASA, and why this should be interesting to those engaged. Our efforts consisted of: staffing 3 of the Maryland Engineering Challenges in Baltimore, MD; judging 3 local science fairs in the Washington, DC area; Presenting our work at 3 open houses for prospective engineering students of the University of Maryland; hosting an outreach presentation for the fraternity Zeta Psi; and giving presentations of our work and demonstrations of our mock-up to thousands of the general public at Maryland Day. The Maryland Engineering Challenges and local science fairs involved interaction with K-12 students, where the Alshain team was given the opportunity to assist in the judging and setup of the event, while also displaying a poster and speaking about Alshain. The open house and fraternity presentations allowed for the Alshain team to educate those already enrolled in an institute of higher learning about the technology and opportunities that result from NASA's research, and all of engineering. Maryland Day is an event open to the general public where they are welcome to explore the campus and learn about the exciting research being performed in their own neighborhood. Here, we educated attendees about the Maryland Neutral Buoyancy Facility, while also displaying and speaking about our LFV. In addition to this, we presented our work to graduate students and members of industry during Preliminary and Critical Design Reviews.

Technology Readiness Levels

Shown below is a summary of the TRL levels of every vital component on board the Alshain.
Table 16: TRL's of the Alshain

Part	Description	Estimated TRL	Known TRL	Final TRL
LIDAR			**7 to 9**	**7 to 9**
Radar			8 to 9	8 to 9
Star Tracker			8 to 9	8 to 9
IMU			9	9
LRS Ranging			4 to 6	4 to 6
Nav Beacon Ranging			4 to 6	4 to 6
LGA Antenna			7	7
HGA Antenna			9	9
Flight Computers	RAD750		9	9
MUX			9	9
Mass Data Storage			9	9
Comm Systems			7 to 9	7 to 9
Status Monitoring Instruments			3 to 9	3 to 9
Video Cameras			4 to 6	4 to 6
RCS	**Cryogenic LOX/LH2 Thruster**	**6**		**6**
Main Thrusters		4 to 6		4 to 6
LOX Tank			3	3
LH2 Tank			3	3
Pressure Tank			9	9
Valve			9	9
Pressure Regulator			9	9
Radiator			9	9
Fuel Cell		4 to 6		4 to 6
Lights			**9**	**9**
Keypad/ Warning Lights			9	9
HMD/ Voice Controls			4 to 6	4 to 6
Joystick			9	9
Debris Shield			9	9

Conclusion

The presumed presence of a replenishable fuel source on the Moon opens up possibilities for lunar flight that would otherwise be economically unfavorable. The characteristics of lunar flight solve the inherent problems found in performing time constrained scientific missions on the Moon. With the exception of some alternatives briefly explored towards the end of the Apollo program, the lunar rover has been the dominant mode of lunar transportation. The lunar flying vehicle provides a significantly more expedient mode of travel than that provided by current rover technology. The Alshain LFV also overcomes the slope and other terrain constraints encountered in rover travel. With the developing plans for lunar research, a lunar flying vehicle is a useful and necessary area of study. The Alshain LFV has been designed to mate with a cargo Altair and is an appropriate complement to the upcoming Constellation program.

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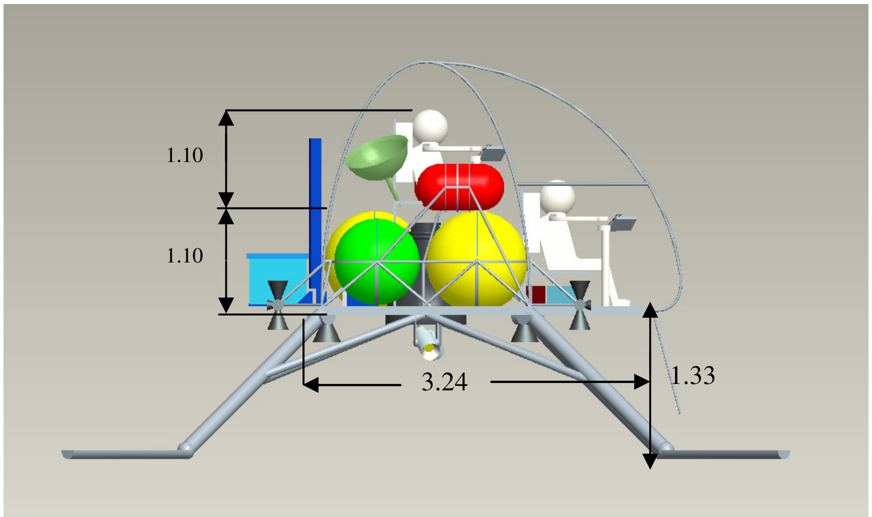
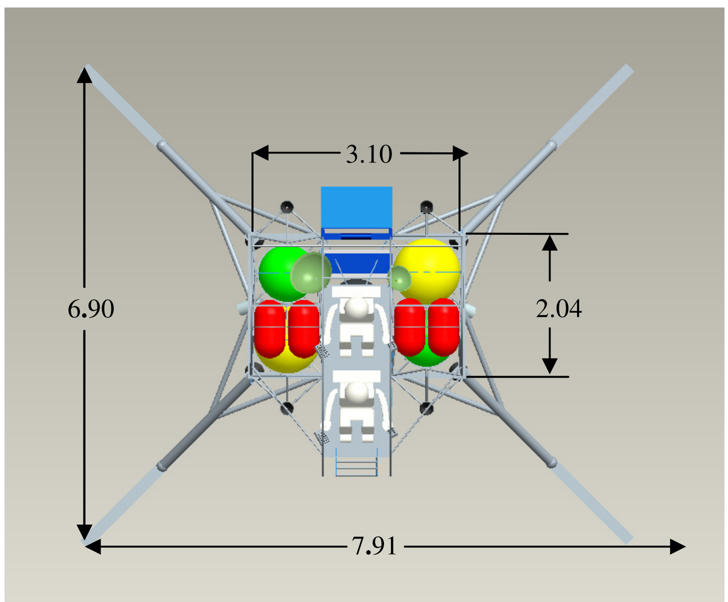
Appendix A: Dimensions





Side and top dimensioned views of the Alshain vehicle:
Note all dimensions are in meters

Appendix B: Hardware

The following pictures show a hardware mockup constructed for human factors testing. A suited subject tested ingress and egress procedures.