SPRITE: Small Pressurized Rover for Independent Transport and Exploration

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The current NASA Exploration Initiative calls for a return to the Moon by 2015. At the outset, missions back to the moon will be of short duration, similar to those of the Apollo era. These will be the first steps in the development and assessment of the technologies necessary for establishing permanent bases on both the Moon and Mars. The major goal of these bases will be to explore their surrounding regions. However, flat and geologically unexceptional areas most easily accommodate the development and construction of a planetary base.

To solve this problem, the University of Maryland design team has designed SPRITE, a rover that allows for the exploration of scientifically interesting areas that are remote to the base. SPRITE is a pressurized rover that allows a crew of two to conduct week-long expeditions to the area around a lunar base. SPRITE and its crew can accomplish this mission through both extravehicular activity and remote, robotic activity. SPRITE significantly increases the science gathering abilities of a planetary base by extending the EVA range beyond what an astronaut can perform operating directly from the base.

1 Introduction

1.1 Concept of Operations

SPRITE's mission divides into three different phases: en-route, post-landing, and surface. The en-route phase begins with the separation of SPRITE and its landing system from the payload fairing of a single Delta-IV Heavy launch vehicle. Burns from a retro stage engine and landing stage thrusters during this phase will successfully land SPRITE on the lunar surface near the lunar base. In the next phase, post-landing, SPRITE will drive from its landing site to the base either autonomously or teleoperated from the base. Once SPRITE reaches the base, astronauts will thoroughly check it for any damage incurred during launch or transit, run a system-wide diagnostic to make sure all systems are running properly, make any necessary repairs, and outfit the rover for the surface phase. Finally, SPRITE enters the surface phase which consists of an indefinite number of three-month lifecycles.

Each three-month lifecycle consists of alternating weeks of outfitting and sorties. During the six "outfit weeks" the base crew will unload all of the waste and science material from the previous sortie, perform routine maintenance and repairs, replenish all of the consumables, and make any other preparations needed for the next sortie. Each sortie will nominally last seven days (though SPRITE will carry enough supplies for 10 days). Two of the seven days will be devoted to driving to and from the base (up to 100 km). The other five days will be devoted to EVA and research. After each three-month cycle, SPRITE will undergo major maintenance and repair. In addition to manned expeditions, SPRITE will also be capable of operating under remote control from the base or Earth or even operating autonomously.

1.2 Design Approach

The design considerations for SPRITE were determined by a set of 33 externally imposed "Level 1" requirements. The key design requirements stated that SPRITE must

- Be capable of independent deployment to the lunar surface with a single Delta-IV Heavy class launch
- Be able to carry two crew members on a nominal sortie of seven days in length
- Be ready for initial lunar operations by 2016
- Systems design shall be conducted in accordance with NASA Standard JSC-28354, Human-Rating Requirements
- Use components at a minimum NASA technology readiness level (TRL) of 3 on Jan. 1, 2005, and shall be capable of reaching a TRL of 6 by the technology cut-off date of Jan. 1, 2010

The design team was divided into six groups: Mission Planning and Analysis, Structures, Avionics, Crew Systems, Power and Thermal systems, and Systems Integration. Each group was responsible for developing the systems and subsystems appropriate to their area of expertise.

2 Overall System Design

2.1 System Overview

SPRITE can operate from a pre-existing base anywhere on the lunar surface. It will launch on a single Delta-IV Heavy and land near the lunar base. SPRITE's primary objective is to assist the base with its exploration of the surrounding region. It can support a two-person crew for a week-long expedition as far as 100 km from the base. The crew cabin (see Fig. 1) houses the crew, consumables, and life support systems. It provides enough space for the crew to live and work during their seven-day sortie. Two fuel cells, supplied by cryogenic LOX and LH2 tanks outside the rover, provide the electrical power required for all systems. The drive system permits a maximum velocity of 15 km/hr. It also allows SPRITE to climb and descend 30° slopes, transverse 20° slopes, and clear 0.5 m obstacles, and can operate in either day or night.

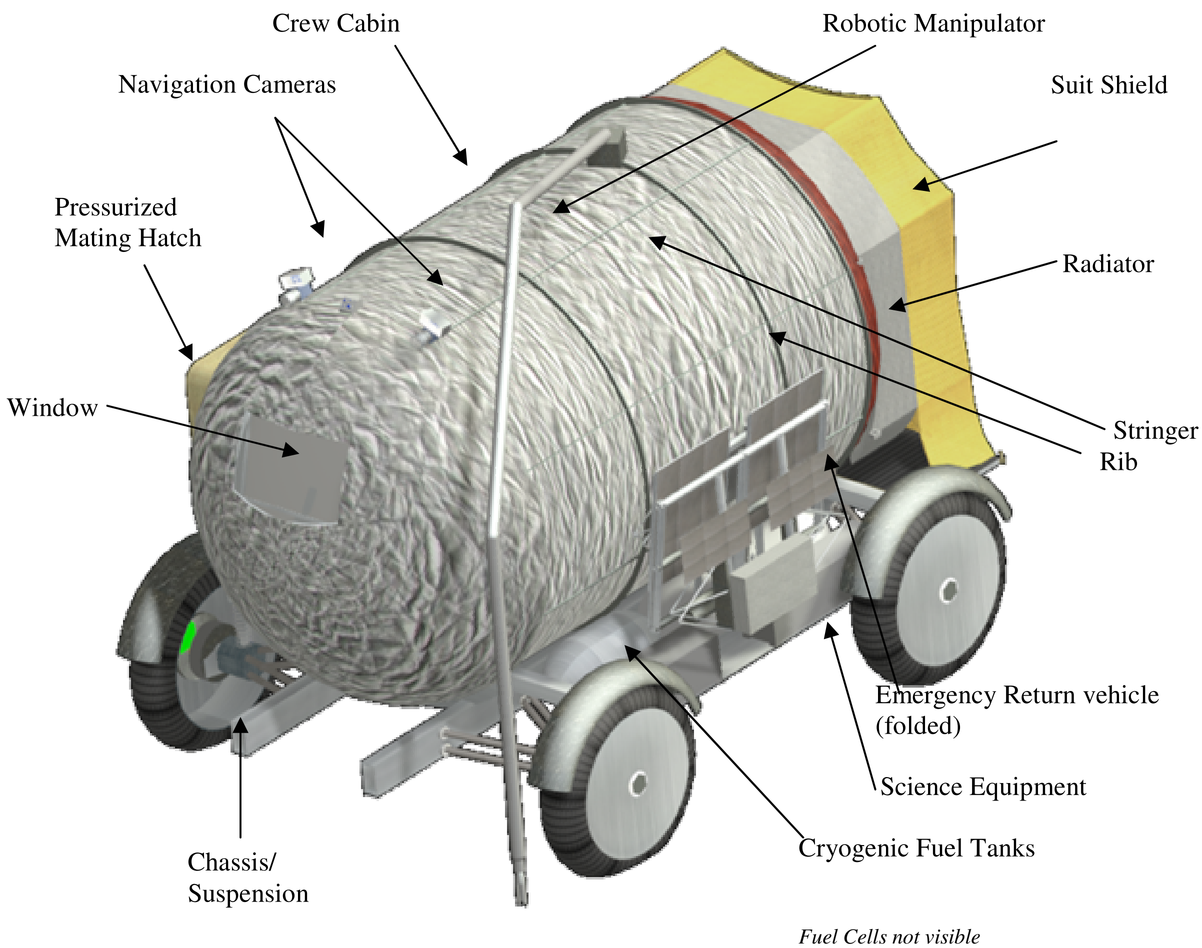

Figure 1 SPRITE System Overview

SPRITE has several contingency options in the event of an emergency. It carries enough supplies for three additional days (beyond the nominal seven). SPRITE has a rocket based emergency communication platform (FLARE) for use in case of an emergency. It also has a small emergency return vehicle, which is a second small, unpressurized rover that can quickly return the crew to the base.

SPRITE's primary mission will be to conduct science and exploration. On each sortie, astronauts will carry out up to five 8-hour EVAs with each being comparable to one Apollo J-Class EVA (the types of EVA performed on Apollo 15-17). Some of the experiments performed by the astronauts will involve such research as mineralogy, internal heat flow, charged particle sensing, and seismology. A robotic manipulator arm with access to SPRITE's entire exterior will be available to aid in science and sample collection as well as assist with normal SPRITE operations.

2.2 Program Timeline

With a planned launch in 2016, all development and production will take place between 2006 and 2015. Based on the Apollo and Space Shuttle programs, design and manufacture was estimated to last about five years and testing to last three to five. Boeing requires at least two years prior to launch to integrate SPRITE into the Delta-IV fairing. This means that production will occur between 2006 and 2011. Testing will occur between 2011 and 2015 with launch planning beginning in 2014. SPRITE will launch and begin operations in 2016.

After arrival and outfitting, SPRITE will have an unlimited operational lifetime on the lunar surface. A critical part of each three month lifecycle is consumables management. A list of all the consumables needed to operate the rover for three months resulted in a total nominal mass of 5800 kg (An additional 500 kg are allotted for emergency items depending on their use on previous missions). The initial launch of consumables will require all 500 kg of emergency consumables, along with the nominal 5800 kg, and 200 kg for space suits, totaling 6500 kg of consumables that will not launch with SPRITE and will need to be provided by the lunar base for initial operations. Each three-month lifecycle will require a cache of consumables be launched to the moon.

3 Vehicle Details

3.1 Crew Cabin Design

3.1.1 Crew Accommodations

SPRITE's cabin size depended on both the ability to fit in the payload fairing of a Delta-IV Heavy and the ability to comfortably house crewmembers ranging from 5^{th} percentile Japanese female to 95^{th} percentile American male. It was determined that a cylindrical cabin with a diameter of 2.5 m would best suit these requirements. The cabin floor rests 0.2 m above the keel, leaving this space open for avionics equipment and life support systems. There is also ample space along the ceiling for storage (see Fig. 2). The floor and ceiling are designed in a grid pattern to allow access to these spaces when necessary. The critical areas of the interior are sized to meet the emergency/contingency condition of a depressurized operable SPRITE and, therefore, must accommodate the 95^{th} percentile American male donned in a spacesuit. These areas include the driving station and exterior hatch.

Beginning at the front end cap, the driving station, on a raised deck, includes all the necessary controls and displays for navigating, driving, monitoring sensors, viewing cameras, and operating the robotic manipulator arm. Proceeding along the right side of SPRITE is the pressurized mating hatch that allows for access to the base or other SPRITE vehicles, the galley that houses all the sanitary and nutrition needs (sink, food dehydrator, and storage), the lavatory, and a storage locker for the crew's personal items. Proceeding along the left side of SPRITE, from the front, is the passenger auxiliary station that allows the second crewmember to view the status of the sensors and also rotate the non-navigational cameras to observe the geological surroundings in search of other notable findings outside the predetermined course. Along the left wall, in between the auxiliary station and the rear end cap are two single bunk beds and a table mounted to the wall. Folded, the table and beds give space to move around and enter/exit the EVA suits. The beds unfold for sleeping and the table unfolds for eating and working. The rear end cap contains the EVA suit hatches (see section 4.1.5).

3.1.2 Environment Control and Life Support System (ECLSS)

The ECLSS is an open-loop system that relies on the lunar base for support. The pressure inside the cabin will be maintained at 8.3 psi (37% oxygen, 63% nitrogen). This allows for quick transfer between the base (assumed to be at one standard atmosphere) and SPRITE, and between SPRITE and the 100% oxygen EVA suit without any pre-breathing. A ten-day contingency-extended mission requires 23.0 kg of oxygen and 1.0 kg of nitrogen to maintain the atmosphere. The boil off rate from the LOX tank, designed to match the rate of oxygen consumption in the cabin, will be controlled by an active cooling system and used to provide breathable oxygen to

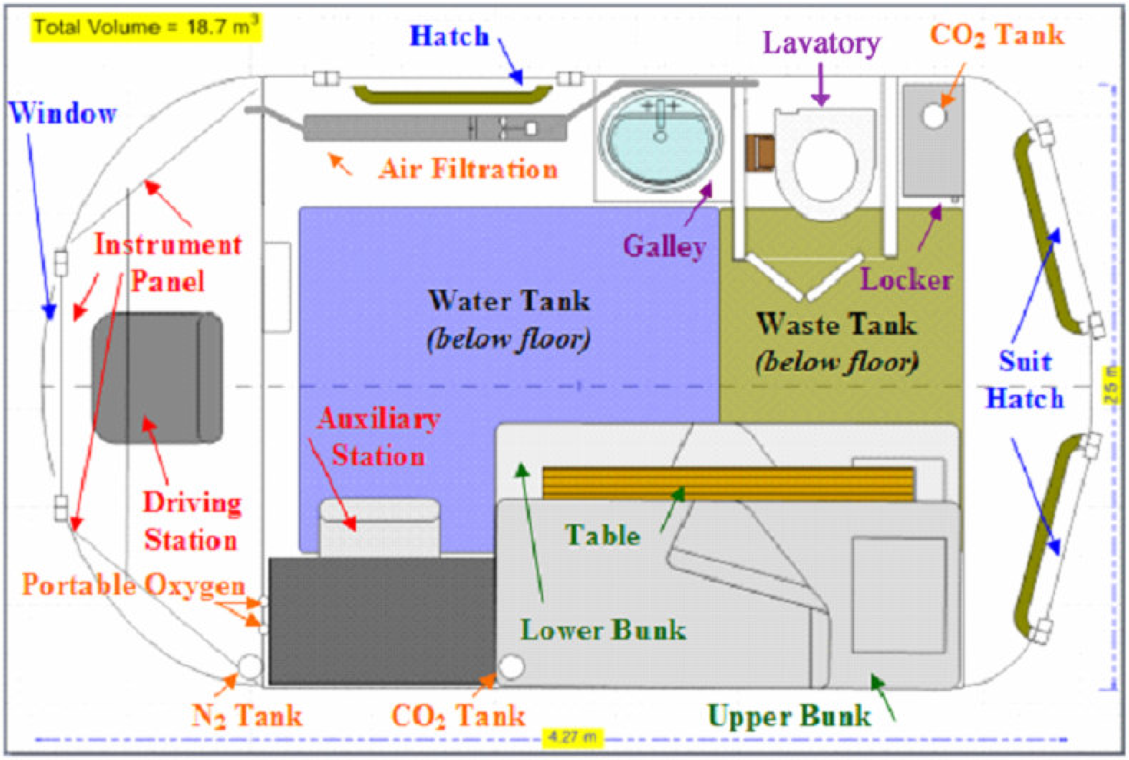

Figure 2 Crew Cabin Layout

the crew. The nitrogen required to maintain the 8.3 psi total pressure will be supplied from a tank stored in the rover.

Lithium hydroxide canisters provide carbon dioxide removal. The non-regenerable open loop system is practical for this short duration mission. The amount of LiOH required to remove one person's average daily output of CO_2 is about 2 kg yielding a total of 40 kg for a seven-day mission with a three-day contingency. An additional 20 kg of LiOH will only be used in the event that the CO_2-based fire suppression system is activated. High efficiency particulate arrestance filter removes other contaminants from the cabin's air.

The crew will also be provided with 40 kg of freeze-dried food for the mission and 150 kg of water (produced by the fuel cells) for drinking, washing, and food hydration while another 100 kg of water will supply the EVA suits with cooling water.

During the 10-day mission the crew is estimated to produce approximately 37 kg of liquid waste, 3 kg of solid waste from urine and fecal matter, and 9 kg of trash. The human waste will be dealt by means of a toilet. All separated liquid waste will be stored in tanks under the floorboard. Liquid waste will not be recycled into drinking water onboard since there will be more than enough water produced by the fuel cell. Solid waste will enter a porous bag that allows air to flow through without allowing odor or bacteria to escape. The bag will then be exposed to vacuum, freeze-drying and deodorizing the solid waste. There will also be a hose inside of the toilet that will remove all unpleasant odors. This hose will lead directly into the air filtering system. This system will remove bacteria, vomitus, trash, fecal odors, hair, skin particles and other body particles from the entrainment air before the air returns to the cabin. The trash will be stored in bags for disposal at the base.[1,2]

3.1.3 Cabin Structure

SPRITE's hull consists of a cylinder with ellipsoidal end caps. The cabin has a diameter of 2.5 m and a length of 2.8 m. The front end cap has a semi-minor axis of 0.9 m and houses the control and driving station. The rear end cap is "flatter" with a semi-minor axis of 0.5 m to allow for hatches to each of the suits.

The skin of the crew cabin was set at a minimum thickness of 4 mm of titanium alloy (Ti-6Al-4V) determined by radiation and micrometeoroid shielding requirements from crew systems. This easily withstands the maximum pressure stress of 30 MPa. Ribs and stringers provide additional structural support for launch and other loads. There are a total of eight stringers placed every 45°, and four ribs, one at each cylinder/end cap interface and the other two placed along the length of the hull.

The window was designed similar to the ISS windows. The first (interior) pane can withstand a 3 kN "punch" load, and serves to protect the main pressure pane from any damage. The main pressure pane can withhold the cabin pressure. The third pane protects the other two panes from outside loads, namely micrometeoroids.

3.1.4 Pressurized Mating Hatch (PMH)

The Pressurized Mating Hatch (PMH), mounted on the side of SPRITE, allows for the transfer of crew and cargo in shirtsleeve conditions to the base and other SPRITE vehicles. The PMH is a hybrid inflatable structure that passively deploys with the assistance of the robotic arm. An androgynous resilient metal seal, held in place by a rigid aluminum frame, establishes and maintains contact with the target object. The main hatch structure consists of an inflatable membrane held in place by an extendible titanium pantograph structure. The membrane consists of an interior Nomex bladder layer, followed by 10 layers of aluminized Mylar MLI insulation, which is protected by an exterior abrasion layer made of Teflon-PTFE fabric. A deployable composite plank serves as flooring during PMH operations and carries all of the loads from people and cargo passing through the hatch. When the PMH is not in use, the plank can be manually folded into three sections and stowed inside SPRITE for later use. A woven Kevlar dust cover protects the seal from dust during normal operations.

3.1.5 EVA Suits/Hatches/Shield

Extravehicular activity egress occurs through an externally mounted suit. Each crewmember's suit attaches to the back of the rover. The suit docks and seals with SPRITE at the backpack similar to the NASA Ames suitport concept[3] (see Fig. 3). The astronaut dons the rear entry suit, closes the hatch, and separates from SPRITE. After completing EVA the astronaut backs into the suitport hatch and climbs out into SPRITE. A Kevlar shroud protects both suits from micrometeoroids and dust during non-EVA operations.

Exterior suits were chosen over interior suits for several reasons: mass, volume, and dust. Exterior suits save mass by eliminating the need for an airlock. Mounting the suits externally also eliminates the need for internal suit storage, which would increase the cabin size by approximately 20 percent. The elimination of the airlock greatly reduces the amount of dust that enters the cabin. During a nominal mission, no part of the internal cabin is exposed to the lunar surface.

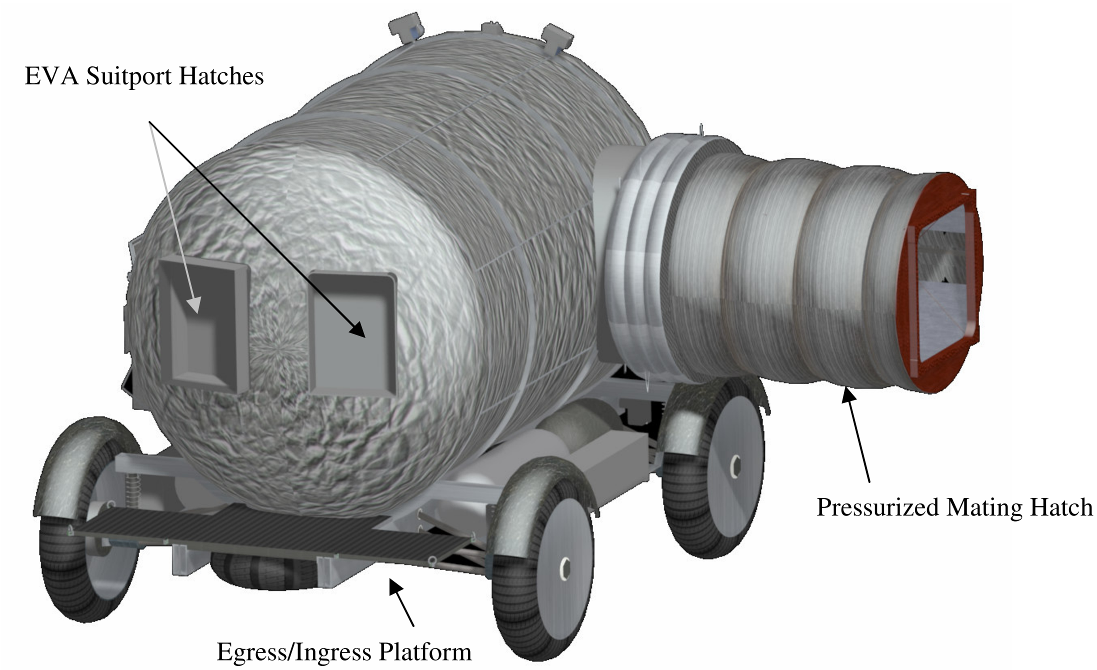

Figure 3 Hatch Locations

3.2 Mobility

3.2.1 Drive System

SPRITE's drive system will allow it to travel at a maximum of 15 km/hr, climb and descend 30° slopes, and traverse 20° cross slopes. It will also allow the vehicle to execute a turn with a maximum turning radius of 10 m at a speed of 10.5 km/hr. The vehicle will be able to come to a full stop from top speed in 1 s over a maximum distance of 4 m. The rover will have the additional capability of towing a second disabled rover in emergency situations. One DC direct-drive high torque motors housed inside each wheel will drive SRPITE (see Fig. 4). Each motor will provides a peak power of 7 kW and a peak torque of 1300 Nm. The rover will be steered by 4 linear actuators that will allow the wheels to turn the 15° required to execute the 10 meter turn. A two part braking system, including dynamic carbon-carbon disc brakes and 4-phase regenerative braking through the DC drive motors, will allow the vehicle to stop quickly in adverse circumstances and gradually while venting heat during normal braking.

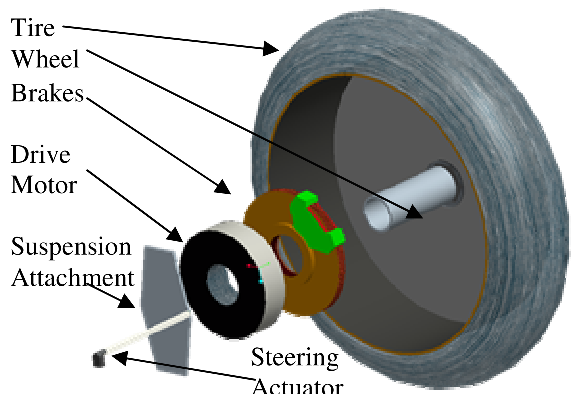

Figure 4 Drive System and Wheel Assembly

The wheels have a 1.2 m diameter to accommodate the requirement of clearing a 0.5 m obstacle. A wheel-width of 0.3 m minimizes power usage and wheel sinkage. The wheel consists of two main parts: hub-rim and tires. The hub-rim design houses the motors inside the hub, protecting them from possible impact during driving. Made from Aluminum 2024 T-4, this wheel is capable of supporting 10 kN in the radial direction, and 3 kN in the transverse direction. The tire is made from a woven mesh of zinc-coated piano wire to increase traction and to absorb a small portion of the energy transferred to the chassis and suspension from impact loads.

3.2.2 Chassis & Suspension

The chassis supports the weight of the rover and external tanks/structures during both launch and surface operations. The chassis consists of two box beams running the length of the rover and two curved beams that cradle the rover and support the suspension and drive systems (see Fig. 5). The titanium alloy (Ti-6Al-4V) construction provides a 0.02 margin of safety during launch conditions and a 0.6 margin of safety under worst case loading during normal operational conditions (see Table I).

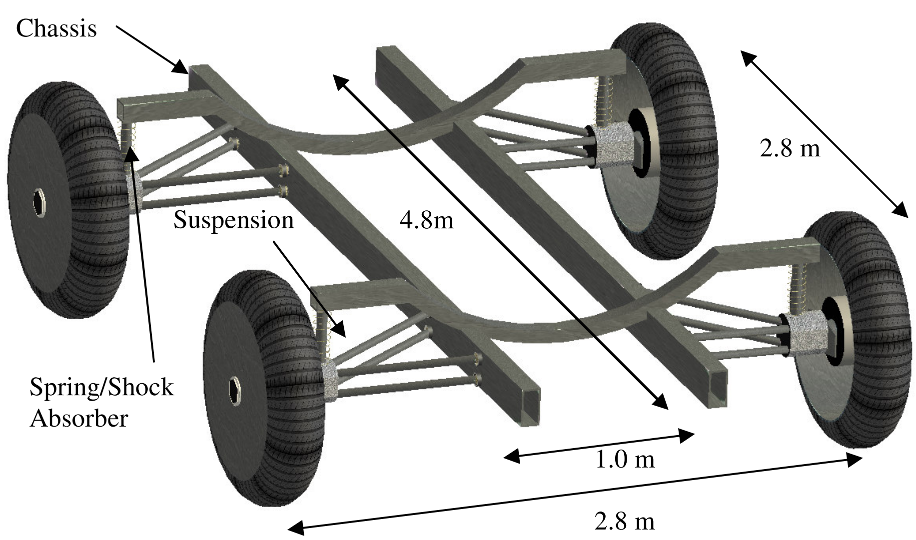

Figure 5 Chassis and Suspension System

SPRITE has a 4-wheel independent suspension. Each suspension assembly consists of two A-frames hinged at the wheel and chassis. This allows the wheel to displace up to 20 cm vertically. A coiled spring and damper absorb dynamic loads caused by driving over the lunar surface. During surface operations, the chassis rides 0.7 m above the surface, allowing for clearance of 0.5 m obstacles and preventing the rover from bottoming out while traversing rough terrain. A wheelbase and wheel stance of 2.8 m is sufficient to keep the vehicle stable in virtually any driving condition. [4,5]

Table I Structural Analysis Overview

Structure	Mass (kg)	Primary Material	SF	Applied Load Source	Applied Load	MOS	Failure Mode
Cabin	435	Ti-6Al-4V	3	Launch	550 MPa	0	Local Buckling
Ribs/Stringers	70	Ti-6Al-4V	2	Launch	450 MPa	0	Bending
Chassis/Suspension	540	Ti-6Al-4V	2	Launch	400 MPa	0.04	Bending
Wheel	38	Al 2024 T-4	2	Collision	150 MPa	0.08	Compression
Landing Gear	108	Al 7075-T6	2	Landing	3.8 MPa		Compression
Rover-Retro Interface	200	Al 7075-T6	2	Launch	220 MPa	0.14	Bending
Retro Structure	500	Ti-6Al-4V/ Al 7075-T6	2	Launch	550 MPa	0	Local Buckling

* All structural analysis was performed with both analytic and finite element methods

3.3 Power and Energy Budget

The energy requirements were derived from the power requirements for each subsystem and an operating time of 240 hours for crew systems and 168 hours for other systems. A margin is maintained to account for presently undetermined losses and miscellaneous components (see Table II).

Table II Power Budget

	Power			Energy		
	Estimated (kW)	Budgeted (kW)	Margin (%)	Estimated (kW-hr)	Budgeted (kW-hr)	Margin (%)
Nominal Driving	5.4	5.9	9.1	116.4	147.5	21.1
Peak Driving	18	20	9.1	31.0	37.5	17.4
Avionics	1.1	1.2	9.1	187.5	206.3	9.1
Crew Systems	2.3	2.6	9.1	519.0	618.3	16.1
Robotic Manipulator	1.0	1.0	0.0	40.0	50.0	20.0
SPRITE	**22**	**25**	**17**	**895**	**1060**	**16**

3.4 Power Systems

The power system for SPRITE consists of a proton-exchange membrane fuel cell system, sized to meet a maximum power requirement of 25 kW. The advantages of using a fuel cell system include very high reliability and efficiency, and the production of potable water. The fuel cell design is based on the GM prototype vehicle Hydrogen 3. The system has a specific power of 940 W/kg and operates with a cell voltage of 0.8 V, a current density of 1 A/cm^2, an operating pressure of approximately 200 kPa, and an operating temperature of approximately 80ºC[6]. The fuel cell system has an output of 34 V with a current of 800 A and an overall stack efficiency of 54 percent[7]. The fuel cells run on hydrogen and oxygen that are stored cryogenically in tanks on SPRITE's exterior. An ordinary sortie will require 57 kg LH2 and 478 kg LOX to power SPRITE for 10 days (nominal mission with three-day contingency).[*,8]

SPRITE's Power Management and Distribution (PMAD) system is based on the above mentioned fuel cell system. A DC/DC converter, mounted next to the fuel cell system, increases the voltage to 230 V. This voltage increase mitigates power loss by 21 percent[†]. This high voltage, high current is carried to a 230 V bus[9]. This bus distributes power directly to the drive system and to another bus for distribution to the rest of SPRITE's systems. SPRITE's drive power comes from an external breaker box leading to four circuits (21 A max) – one for each wheel/motor system. For other systems' power, the first step is a DC/DC converter which brings the voltage down to 28 V. This voltage is then split into internal and external breaker boxes. The internal system consists of two circuits, one for part of the avionics budget (25 A max), and one for the crew systems budget (108 A max). The

[*] While the LOX and LH2 are consumables that the base will provide, SPRITE must launch with 11 kg LH2 and 87 kg LOX to provide enough power for SPRITE to operate before it reaches the lunar base.

[†] $P_{loss} = P^2R/V^2$

external system consists of the remainder of the avionics budget (16 A max) and the Science Instrumentation budget (36 A max).

SPRITE's emergency battery system contains 120 batteries connected in parallel. The total battery package has a mass of 19 kg and can output 3 kW-hr at 108 A and 6 kW peak power. Charging and discharging is controlled by a battery control unit (BCU). The BCU monitors the battery for voltage, temperature, and pressure and then commands the battery bidirectional power converter (BPC) to charge or discharge the battery based upon preset temperature/voltage and pressure/voltage curves. The BPC also has a manual override to allow the crew to charge/discharge the batteries.

The emergency battery system is primarily available to crew systems. The power from the battery system is routed directly to crew systems through a bus switching unit (BSU). The BSU monitors the health of the main 28 V bus and in case of main power failure, it automatically switches (manual switching is possible) over to the emergency system 28 V bus, powering crew systems in case of emergency.

3.5 Thermal Systems

The exterior of the vehicle is covered with 20 layers of 380 micron aluminized Mylar (mass of 94 kg) to protect it from the harsh thermal environment. Active cooling is accomplished by running water-filled copper heat pipes (mass of 110 kg) along the avionics and into an aluminum heat exchanger (surface area of 2.5 m^2). The excess heat is then dissipated to the exterior of the vehicle through an aluminum radiator (surface area of 1.5 m^2) which is coated with white zot paint to increase its emissivity. The thermal system is able to dissipate 1 kW of heat.

4 Avionics

4.1 Communications

Because SPRITE's travels will bring it over the base's horizon, its communications must be relayed. If based on the near side of the Moon, Earth's Deep Space Network will perform these relays. If based on the far side, a satellite in halo orbit about the second Earth-Moon libration point will perform them. Besides transmitting voice and data to the base, SPRITE also has the capability to upload one channel and download two channels of HDTV at a bi-directional rate of 10 Mb/s directly to Earth. SPRITE's high gain antenna (0.5 m diameter) will transmit and receive these communications. During EVA, SPRITE and the astronauts communicate through a low gain antenna (0.1 cm diameter). To ensure that the network operates optimally, the link budget (see Table III) has a link margin of 3-6 dB.

Table III Communications Link Budget

	SPRITE to Earth/Base	SPRITE to EVA
Antenna Type	High gain	Low gain
Band	Ka	UHF
Frequency	20 - 25 GHz	0.9 GHz
Power Output	10 W	20 W
Data Rate	50 Mb/s	50 Mb/s
Link Budget	3 - 6 dB	4 dB

4.2 Surface Guidance Navigation and Control

In order for SPRITE to navigate safely up to 100 km away from the lunar base, it must know its position to a high degree of accuracy. This is accomplished via a hybrid stellar, landmark, and dead reckoning navigation system. A star tracker gives SPRITE a rough estimate of its position on the lunar surface, and can also act as a backup in the event of other navigation failures. This first position estimate is passed on to the landmark navigation system, which takes pictures of the horizon with an exterior camera and correlates them with an onboard database of lunar topography (provided by the 2008 Lunar Reconnaissance Orbiter). These maps will also be used during the sortie planning process to keep SPRITE on accessible terrain. In between landmark navigation fixes, the rover updates its position using wheel odometry and a millimeter-wave radar which can detect and adjust for wheel slippage. To prevent roll over, sensors monitor the vehicle's stability and regulate its movement to act within its safety envelope.

4.2.1 Obstacle Detection and Avoidance

Obstacle detection and avoidance is an important task during direct driving, teleoperative, and autonomous control modes. SPRITE detects obstacles in four ranges: mid-range, near-range, immediate-range, and rearward. The mid-range system monitors 21-50 m ahead of the vehicle for large obstacles and dangerous slopes. It consists of two stereo camera pairs, one of which has night vision capability. Another stereo camera pair performs near-range obstacle detection and covers the area within 6-21 m ahead of SPRITE. A pair of 200 W headlights allow for nighttime operations. The mid-range and near-range camera images will be pre-processed by vision front-end processors to generate stereo disparity maps in real-time for output to the obstacle avoidance system. Upon detection of an obstacle, SPRITE will slow down so that the immediate-range system can take over and analyze the situation. The immediate-range system uses a 3D laser scanner to sweep over distances 0.5-6 m ahead of SPRITE. Rearward obstacle detection will use the same laser scanner. These four subsystems feed into an autonomous driving computer with a path planning algorithm onboard. Safe paths around local obstacles can be generated in approximately 0.5 seconds. These paths are output to the navigation computers, which generate drive and steering commands.

4.3 Computers

One RAD6000 33 MHz general-purpose computer will be responsible for performing error checking on the redundant navigation computers as well as redundant sensors. Two RAD750 166 MHz navigation computers (1 primary, 1 redundant) will be used to format navigation data for output to visual displays, determine SPRITE's physical state, process path commands from the autonomous driving computer, command the drive-by-wire system, process landmark navigation, and process crew route planning. One 800 MHz SCS750 autonomous driving computer will process the vision front end processor's stereo disparity maps, as well as the range maps from the laser scanner computer, and compute safe path commands for SPRITE to follow. One RAD750 obstacle-processing computer will process the 3D laser scanner data to build and export range maps to the autonomous driving computer. Another RAD750 computer will be used to control the robot arm and process the output of the robot arm's stereo camera pair's vision front-end processor. Two laptops will be supplied for the crew's personal use during sorties.

4.3.1 Data Storage

Landmark navigation will require 500 MB of storage, science data will require 14 MB, and the topographic maps will require 4 GB of storage. Two redundant Astrium GmbH non-volatile single board mass memory boards with capacities of 1 GB and transfer speeds of 250 Mbps will store all data except the topographic maps. The topographic maps will be stored on a 4 GB board. External data backup will be accomplished with a Blu-Ray optical disc recorder (25 GB capacity per disc).

4.3.2 Networks

SPRITE's primary network will handle data between the main computer, the navigation computers, navigation and guidance instrumentation, cameras, visual displays, and data storage devices. The estimated data throughput for this network is 57.6 Mbps. Spacewire will be used as the primary network data bus, at a data rate of upwards of 200 Mbps, with full duplex operation, and a bit error rate of 10^{-14}. A vehicle/crew health network will monitor vehicle and crew health sensors with update rates of 1 Hz, and will generate an estimated network data throughput of 1 kbps. A dual-redundant Mil-Std-1553 bus with an effective data rate of 300 kbps and bit error rate of 10^{-12} will carry the data between the sensors and general-purpose computer.

5 Lunar Operation

5.1 Typical Sortie

A nominal SPRITE sortie will be seven days long and will explore several different areas of interest away from the base. On the first day, the crew will depart from the base and drive to the first area of interest (up to 100 km). On each of the next five days, the crew will use on board cameras and sensors as well as EVA to survey the area. They will perform scientific experiments and collect samples for a more detailed analysis at the base. At the end of each day, the crew will drive up to 10 km to the next area of interest for exploration on the next day. At the end of the sixth day, the crew will stay at the final survey site for the "night" and return to the base on the seventh day.

In terms of a day-by-day breakdown, the first and last days involve large 100 km treks to and from the base to the proposed EVA area. The daily schedule for these two days is fairly streamlined and void of a great deal of scientific documentation. On the other hand, the five EVA days requires more detailed scheduling. Important daily activities include eating, sleeping, hygiene, pre and post EVA activities, repositioning, personal time, and an 8-hour EVA. More than half of the day is spent on EVA and sleeping but the rest of the tasks are relatively brief in comparison. Table IV illustrates a model for an EVA day breakdown going from midnight to midnight Earth time.

Table IV Sample Daily Schedule

Time Segment	Activity	Total Time (hrs)
00:00 - 06:00	Sleep	6
06:00 - 06:30	Hygiene	0.5
06:30 - 07:15	Breakfast	0.75
07:15 - 07:45	EVA Prep	0.5
07:45 - 15:45	EVA	8
15:45 - 16:15	Doff suit	0.5
16:15 - 16:45	Hygiene	0.5
16:45 - 17:00	Review of EVA Activities	0.25
17:00 - 17:45	Dinner	0.75
17:45 - 18:45	Reposition	1
18:45 - 20:45	Complete Earlier Notes	2
20:45 - 21:45	Personal Time	1
21:45 - 22:00	Hygiene	0.25
22:00 - 00:00	Sleep	2

5.2 Science Objectives

5.2.1 Science Operations

SPRITE's science payload and EVA capabilities allow each of the five EVAs performed on a sortie to match or surpass the scientific return of a typical Apollo J-Class EVA (Apollo 15-17). While required instrumentation would differ depending on which region of the moon SPRITE is based in, its core scientific complement addresses priorities identified in the Lunar Surface Science Working Group's "Lunar Surface Exploration Strategy" (1996). These priorities include seismometry, heat flow, magnetometry, atmospheric monitoring, and sample collection. Besides collecting 100 kg of samples for return to base per sortie, astronauts will also set up an instrument hub similar to the Apollo Lunar Surface Experiment Package. This 25 kg unit is powered by a radioisotopic thermal generator and once in place, can transmit experimental data to Earth for several years. SPRITE and its passengers will also perform documentation activities and take geological surveys. A thermal emission spectrometer mounted atop the crew cabin maps the surrounding mineral distribution, and during EVA astronauts will create HDTV and digital photographic records of the site they are exploring. Upon completion of a sortie, further analysis of samples will begin at a base science laboratory.

5.2.2 Robotic Manipulator

The robotic manipulator allows the crew to interact with the environment and SPRITE's external structures without performing an EVA. Mounted atop SPRITE, the arm has a total reach of 7 m and a workspace that includes the entirety of SPRITE's exterior. It has seven degrees of freedom allowing the end effector to reach any point in the workspace from any orientation.[10,11] A brushless DC motor with a harmonic drive actuates each of the seven joints[12]. The manipulator can deploy science equipment, collect samples, deploy the docking hatch, and inspect the EVA suits or SPRITE for damage and make minor repairs. The arm has the ability to change end effectors. Each end effector will be stored in the arm's base on top of SPRITE. A gripper end effector will allow the arm to grasp samples and SPRITE components. A rock abrasion tool can also be mounted on as well as any other tool that may be required on a sortie.

The manipulator will have a small network containing the control computer, a stereo camera pair, seven controllers, and seven joint angle sensors (one at each joint), and 2 CCD cameras (on the shoulder and elbow). To minimize the instability that can result in the time delay, and to reduce the operator's mental fatigue during operations from the base or earth, the manipulator was designed to operate under supervisory control. In free space operation the manipulator relies on the accuracy of the encoders that keep track of its relative position with respect to the rover. These values are compared to a map of the rover's external features to serve as a collision avoidance system. To give the operator of the arm a view of the robotic arm motion, one camera is placed at the shoulder and another at the elbow. When using the end effector, a stereo pair is used to provide visual feedback to the computer to determine location of target and whether contact has been established.

5.3 Emergency Procedures

SPRITE has several means of returning the crew safely to the base. In the event of a loss of cabin pressure, the crew can don their suits, enter SPRITE through the main hatch and drive back to base in their suits. In the event that SPRITE's driving system fails, the crew will contact the base to coordinate a rescue. In the event of a communications failure, the crew will launch a rocket based emergency communication platform (FLARE) to regain short-term communication with the base. If any failure occurs that endangers the crew's life, they will abandon SPRITE and return to base in the emergency return vehicle.

1. Flying Locator and Assistance Requesting Equipment (FLARE)

FLARE is an emergency communications package that relays voice and data traffic directly between SPRITE and the base. FLARE is to be used in the event of a critical life support failure or core avionics failure.

FLARE utilizes a canister launched solid rocket to propel a radio relay package above the lunar surface so that it is in line of sight of both SPRITE and the base. FLARE reaches a maximum altitude of 65 km and can transmit at any altitude above 2.8 km, giving it a total relay time of 9.5 minutes. FLARE operates two channels at 450MHz. One is a continuous voice relay channel and the other is a data channel that loops SPRITE's last known position and critical sensor information. Receipt of a FLARE signal at the base immediately triggers an alarm and activates recording mechanisms on both channels. The astronauts can activate FLARE from either within the cabin or from EVA utilizing the SPRITE-to-EVA communications path. FLARE uses three low-gain antennas that evenly spaced along the length of the package so that one antenna is in sight of each target at any time.

2. Emergency Return Vehicle (ERV)

In the event of a life threatening failure(s), there is an auxiliary rover attached to the side of SPRITE providing independent transport that returns the crew to the base quickly and safely. The ERV system is self-contained and independent of SPRITE. The ERV is optimized for a two person, 8-hr return, but carries enough consumables for 10 hrs. The seating is side by side with a control station located between the seats. On the control station are a 2-DOF joystick and a navigation box. The drive controller is located on the center beam, behind the seat. The battery is mounted on the chassis toward the front, while the consumables tanks are mounted near the back. When driving, the ERV has a length of 3.1 m, a width of 2 m and a height of 1.7 m. The total mass of the ERV is 245 kg, with a rolling mass of 677 kg.

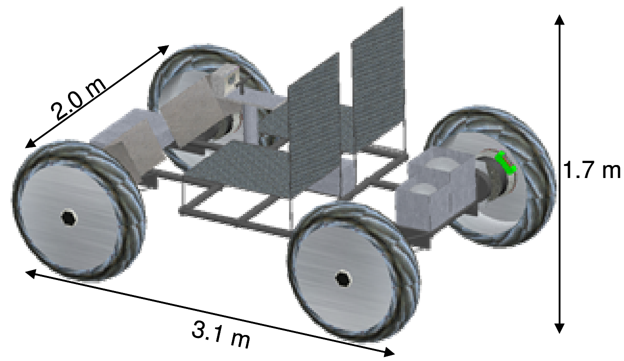

Figure 6 Emergency Return Vehicle

The ERV has four 0.5 m diameter wheels each with its own suspension and motor. The ERV Suspension is based off the Apollo Lunar Rover suspension system. Two parallel triangular arms attach the chassis to the traction drive. The load is transmitted through the arms to separate torsion bars. Linear fluid dampers limit the vertical movement of the ERV. The wheels and motors are able to detach from the suspension system for storage.

The ERV is attached to the side of SPRITE by folding it in thirds. The front and back chassis sections fold inward and the chairs and tank holders both collapse. The control station detaches and is hooked onto the back. In the folded configuration, the ERV has a length of 1.3 m, a width of 1.6 m, and a height of 0.8 m. In order to fit the ERV in the launch vehicle, it must be launched disassembled in two boxes located within the landing structure: four wheels will be in one box, all other components in a separate box.[13]

3. Fault Tolerance

SPRITE maintains two-fault tolerance for all foreseeable crew-threatening events. Figure 7 outlines the possible life-threatening failures and their resolutions. There are five main areas for failure: critical communication failure, critical life support failure, critical mobility systems failure, critical navigation failure, and critical power failure. If any failure falls into one of these categories, the crew will begin emergency procedures.

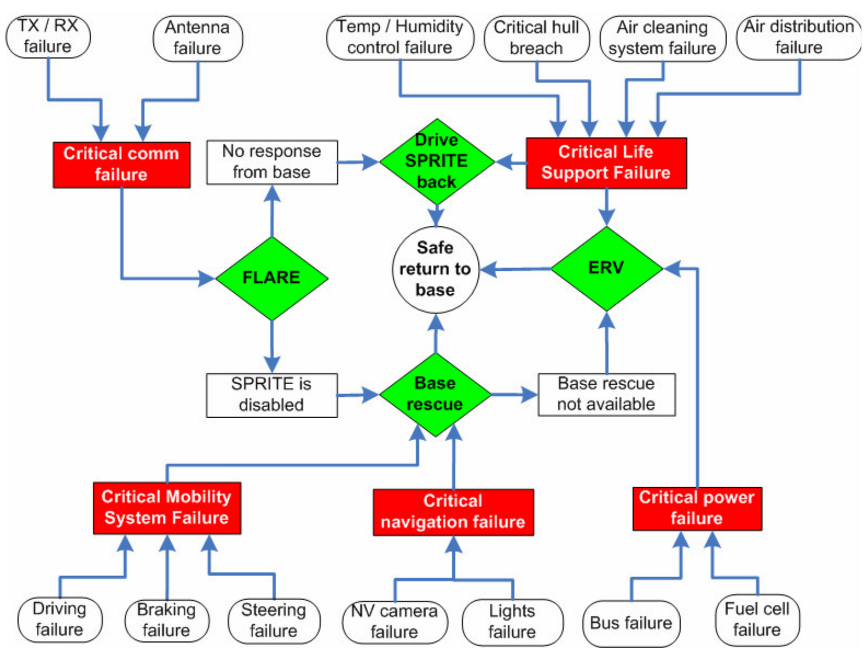

Figure 7 SPRITE Fault Tree

5.4 Base Operations

The lunar base will provide all consumables for a nominal sortie (see Table V). There are two main phases of base operations. First, the base provides the outfit and assembly of key components of SPRITE upon its landing on the moon. Second, the base will replenish all consumables between missions and perform any maintenance or repairs necessary to the vehicle. An umbilical from the base will provide 2.5 kW of power for basic avionics and life support. The base will also have a matching pressurized hatch to allow for shirtsleeve transfers from SPRITE to base.

On a post-landing outfit, the base will need to perform several key functions: refill all consumables (such as liquid oxygen, nitrogen, liquid hydrogen, and lithium hydroxide), assemble the emergency return vehicle (ERV), attach the robotic manipulator, outfit the scientific instruments, and attach space suits. These functions will be performed as soon as SPRITE arrives at the base, prior to the first sortie. On the week between sorties, the base will be expected to refuel and refit all consumables for the next sortie, inspect all major SPRITE components for damage, unload all rock samples, and install the next crew's EVA suits. The base will conduct all of the detailed analysis of the samples collected and observations made during each sortie.

Table V Supplies Provided by Base

Item	**Mass (kg per sortie)**
LH2	60
LOX	500
Nitrogen	1
Food	40
Initial Water Supply	13
CO_2	10
LiOH	60
HEPA Filters	19
Emergency Batteries	20
Science Equipment	332
ERV Batteries	49
ERV Consumables	22
Total	**1126**

6 Deployment

6.1 Launch Vehicle Integration

The SPRITE launch package consists of SPRITE, a landing stage (that carries SPRITE to the lunar surface), and a retro stage that takes SPRITE into lunar orbit and begins the descent (see Fig. 8). The descent stage attaches to SPRITE's underside at the wheels and chassis. It also carries the disassembled ERV, which will not fit in the fairing fully assembled. This landing package rest vertically in the fairing and attaches to the retro stage at the crew cabin, chassis, and landing platform.

The retro stage consists of a retro engine, LOX tank, and LH2 tank. The interface from the LH2 to the Rover interface is a 30^o symmetric sweep every 90^o about the axis of the payload. The next section which is the interface between the LH2 and LOX tanks consist of a 5mm thick aluminum skin and eight stingers. The stringers are made up of hollow circular cylinders which maximize the mass moment of inertia per stinger allowing for a decrease of overall mass. The bottom LOX fairing supports the most load of all the structural elements, and must survive launch and function as the thrust structure for the decent engine (Table II outlines the thrust structure analysis). All of these members were sized to withstand the launch loads of 6 g's along the Delta-IV axis and 2.5 g's laterally.

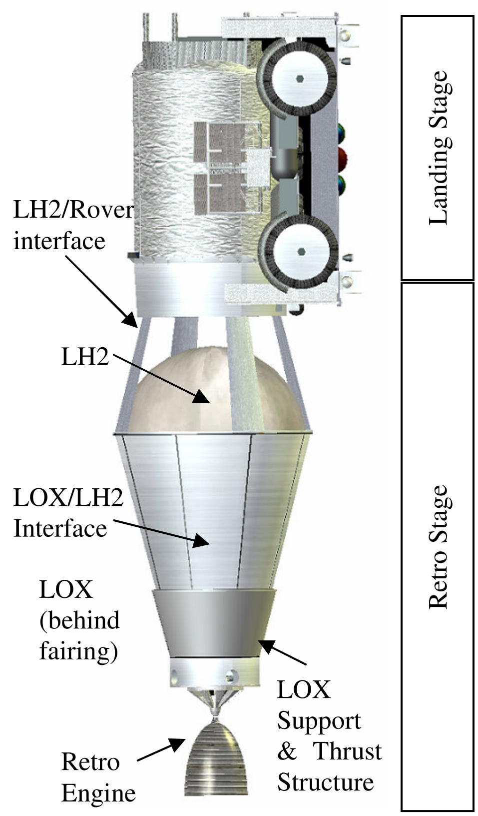

Figure 8 Launch Configuration

6.2 Trajectory Planning

The Delta-IV Heavy can place up to 9,960 kg into translunar orbit. Separation from the Delta-IV second stage engine does not occur until after the remaining fuel has been expended and SPITE has been placed on its translunar trajectory. The trajectory is optimized to minimize the total ΔV, thereby reducing the amount of propellant required and the size of the propulsion system as a whole. All other things being equal, the trajectory optimization routine should additionally search for the shortest time of flight, leading towards an approach of the Moon near perigee. Time of flight becomes a concern because many systems including telemetry, active cryogenic cooling, attitude control, and all the avionics involved in space flight will need to be kept active during the entire transit phase.

The selenocentric maneuvers follow the three tiered Apollo style approach from low lunar parking orbit to lunar descent orbit followed by a propulsive soft landing. This approach allows time for the guidance, navigation and control systems to perfect the landing trajectory ensuring safe and accurate delivery of SPRITE's landing system to the intended lunar coordinates. Unlike Apollo, SPRITE has two propulsion stages responsible for landing the vehicle. SPRITE's retro stage makes use of a highly efficient LOX/LH engine to accomplish lunar orbital insertion as well as to overcome the orbital velocity on landing. The initial retro burn occurs at an altitude of 5.2 km. At 300 m, the retro stage separates and the landing stage completes the landing. The landing stage features a highly redundant and controllable set of four corner-mounted pressure-fed hypergolic engines, which provide the thrust for the final 300 m of the descent. After designing and running a landing simulation SPRITE's estimated landed mass is 4250 kg, inclusive of the inert mass required on the landing craft.

Table VI Retro/Descend Burn Summary

BURN / MANEUVER	SYSTEM	ΔV [km/s]	MP [kg]	ΔT [s]
Lunar Orbit Insertion	Retro	0.816	1682	101
Descent Orbit Insertion	RCS	0.022	63	450
Propulsive Descent Retro Phase	Retro	1.71	2652	160
Propulsive Descent Landing Phase	Landing	0.099	172	76

6.3 Descent and Landing

6.3.1 Propulsion System

The retro stage of the landing module will use the RL-10A-3A as the primary retro thruster. It runs on LOX/LH2 and can generate 73 kN of thrust with a 444 s specific impulse. Accompanying this engine will be four hydrazine RCS thrusters. The purpose of this is to allow for course correction during its journey to the Moon. The retro stage will detach from the rest of the module once its burns have been complete and the remainder of the landing procedure will fall to the landing stage. This stage is comprised of 16 RCS thrusters, and four landing thrusters called Multi-Use Thrusters (MUT)[14]. These thrusters deliver a maximum thrust of 6 kN. MON/UDMH will be used as the propellants for this stage. The MUTs provide pitch and roll control, while the RCS engines provide yaw control and fine-tuned pitch and roll control. Translational control is achieved through banking motion. The MUT fuel lines are cross-fed for fault tolerance, so up to 2 diagonally opposed MUTs can be lost without a landing failure.

6.3.2 Guidance Navigation and Control

During descent and landing, fiber optic inertia measurement units (IMU) sense angular acieration rates. Star trackers detect star patterns and magnitudes. Guidance computers use the IMU and star tracker data to calculate its position, velocity, acceleration and attitude. The landing control system consists of three microwave scan beam landing systems, two radar altimeters, and two earth-moon limb sensors. The microwave landing system finds SPRITE’s position relative to the lunar base while the altimeters and limb sensors gather altitude and attitude data. This allows the guidance computer to execute the appropriate steering commands to ensure a soft and accurate landing.

Landing hazard avoidance will be performed via stereo from lander motion. The lander will enter into a hovering phase 200 m above the lunar surface and take two images of the landing area approximately 70 m apart to generate a stereo image. SPRITE’s autonomous driving computer will be used to construct a digital elevation map from this stereo image and select a safe landing area. The lander’s position will then be recalibrated with respect to the stereo image using an absolute distance to ground measurement provided by one of the onboard laser altimeters. The lander will then descend to a safe landing area.

6.3.3 Landing Structure

The landing structure consists of a rectangular L-beam platform 4.7 m by 3.4 m, landing legs, deployable ramps and the landing propulsion system. There are four landing legs, one placed at each corner of the platform on a 45° angle, initially 1.3 m long. The landing legs were designed to satisfy level 1 requirements that SPRITE land with a 1 m/s and 0.5 m/s residual vertical and horizontal velocities respectively, 0.5 m obstacle and 10° slope anywhere in the landing footprint. The landing legs must survive any and all combinations of these possibilities. The legs consist of an upper (0.9 m) and lower (0.9 m) strut, Spiralgrid ™, a crushable aluminum honeycomb insert (0.4 m, crush strength of 6.56 MPa) and a pivot foot to accommodate the uncertain terrain. The lower strut is contained within the upper strut to crush the aluminum honeycomb during landing to absorb kinetic energy. All components, except for the honeycomb insert, are made of Al 7075-T6. This material was chosen because of the strength-to-weight ratio and mass restrictions. Upon impact the honeycomb crushes to absorb kinetic energy. After landing, four ramps, aligned with the wheels of SPRITE, deploy to provide two directions for exit. The ramps are 1.8 m long L-beams and provide, at most, a 30° incline for SPRITE to get to the surface.

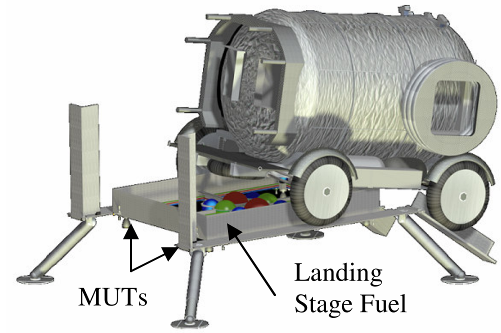

Figure 9 Descent/Landing Stage with Legs and Ramps Deployed

7 Conclusion

7.1 Cost Analysis

In order to estimate a cost for the SPRITE program, several different NASA cost-estimating relationships (CER) were used. Each was chosen based upon its ability to best estimate the cost for each of SPRITE's main components, namely the SPRITE vehicle, the ERV, the robotic manipulator, the landing craft, the retro engine, and launch.

The SPRITE vehicle utilized the Advanced Missions cost model provided by NASA Johnson Space Center[15]. The ERV was broken down to components and estimated using component level CER's from NASA Goddard Space Flight Center. The landing craft also used NASA Goddard CER's, but estimating was done on a vehicle-level. The robotic manipulator was the only source that did not have a cost associated with a cost model. In this instance, a relatively similar robotic manipulator was found with an associated cost, and this cost was used for the SPRITE system. For the retro engine, and the MUT engines on the landing craft, the cost was estimated using the NASA JSC Spacecraft/Vehicle level model, utilizing the liquid rocket engine option. This allowed an estimate of the production cost, which is the only variable that was taken into account, because these engines have already been developed (see Table VI). The total development and production costs will be approximately $ 2.9 billion, with this cost spread over the next 10 years using a standard beta costing function with a maximum annual cost of $500 million in 2008. Additional costs of launch and re-supply will also apply to the program as a whole.

Table VII SPRITE Cost Estimates

Program Component	**Estimated Cost ($M2005)**
SPRITE Vehicle	2270
ERV	11
Landing Craft	36
Retro Engine	5
Robotic Manipulator	300
Launch	250
TOTAL	**2872**

7.2 Outreach

The University of Maryland team made several efforts throughout the project to increase public awareness of SPRITE and lunar exploration. Design reviews during the project were open to the public. University faculty, alumni, and engineers from NASA Goddard and other area companies attended a Preliminary Design Review on March 14. Faculty, alumni, and local professionals were also invited to attend a Critical Design Review on April 21.

On April 30, the university sponsored its annual Maryland Day. On this day as many as 30,000 people from all over the country explore the campus and all that it has to offer. The team set up and manned a poster display at the Space Systems Laboratory (one of the most visited labs on Maryland Day). Hopefully, our efforts helped in renewing interest in further manned space exploration.

Figure 10 Team members Answer questions about SPRITE during Maryland Day.

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