Small Lunar Exploration and Delivery System Concept

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This paper describes an architectural concept for a Small Lunar Exploration and Delivery System to operate as a platform for emplacing payloads into lunar orbit and onto the lunar surface, while providing mobility for surface exploration, science, and infrastructure. The concept leverages emerging services that are capable of delivering payloads to Low Earth Orbit (LEO), while utilizing new and old technologies to build a platform for transfer to Low Lunar Orbit (LLO). Advances and miniaturization in avionics, navigation, power, and propulsion systems enable a unique opportunity to develop a system that is both capable of landing on the lunar surface and providing surface mobility with the same system.

Nomenclature

\( \textit{deltaV} \) = change in velocity, m/s

\( \textit{Isp} \) = specific impulse, s

I. Introduction

Government and commercial efforts from around the world are racing to send exploration and scientific spacecraft back to the Moon. NASA is investigating the use of small missions to perform site surveys, environmental science, emplace early infrastructure, and provide testbeds for technology development projects¹. Space ventures are expanding from the public sector out to the private sector. The Google Lunar X-Prize (GLXP)¹⁰ will award the first privately funded team to successfully send a robot to the Moon, travel 500 meters over the lunar surface, and perform a series of tasks on the lunar surface.

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surface and transmit video, images, and data back to the Earth. Companies around the world are raising private funds to fuel innovation in technology and establish space infrastructure. There is a need to provide an architecture that will enable the goals of these missions by providing a cost-effective and repeatable system for delivery and exploration.

The SpaceX Falcon launch vehicle\textsuperscript{11} and EELV Secondary Payload Adapter (ESPA)\textsuperscript{12} provide new opportunities for low-cost access to space for small payloads. These systems are slated to deliver significant mass to low-Earth orbit (LEO) and Geosynchronous Transfer Orbit (GTO), which can send a lunar transfer vehicle well on its way to low-lunar orbit (LLO). A standardized platform can provide power and communications from Earth to the Moon. This same platform can also be placed into lunar orbit with a communication and navigation payload, or deliver a landing system that will descend to the lunar surface. A flexible platform that provides transfer, orbit maintenance at LLO, and a delivery system for lunar landing and surface systems will make it easier to sustain a continuous build-up of missions and infrastructure for exploration and utilization of the moon.

Advances in avionics, navigation, power, and propulsion systems have made small landing systems feasible. These systems can be developed to provide flexibility for numerous mission types, including science platforms and technology testbeds. To achieve these mission goals, our concept utilizes the lander as the mobility system by “hopping” from the landing location to other points on the lunar surface. Previous missions have used landing platforms that deliver rovers for planetary exploration. Rovers have several disadvantages that are mitigated by the hopping concept. Rovers introduce an additional system above the lander, must egress from the landing platform, and have limited mobility once on the surface. A hopper uses the same propulsion system for landing and hopping, mitigating the dangers of egress. The hopper is capable of travelling long distances and over large obstacles or into steep craters that rovers would not be able to do. Hoppers also make precision landings more accessible. Precision placement is no longer only a function of landing accuracy, but is enhanced by the ability to move the entire platform quickly, safely, and accurately to another location. This capability enables the platforms to act as navigation beacons, site surveyors, and sample collectors over diverse terrains and multiple locations.

This paper will describe the mission architecture and description to provide cost-effective commercial access to lunar orbit and the lunar surface using a lander/hopper architecture being developed by the Next Giant Leap (NGL)\textsuperscript{13} team.

II. Design for the Google Lunar X-Prize

The Google Lunar X-Prize was developed to foster innovation and entrepreneurship by the private sector to develop vehicles for planetary exploration. To date, projects that have landed on planetary surfaces have been heavily funded by governments. The basic rules of the GLXP\textsuperscript{14} are simple:

- Land on the moon
- Traverse 500m once on the lunar surface
- Send back video, images, and messages from the moon

The contest fosters innovation by creating a new paradigm for science and exploration. Instead of large, costly missions that pack many science payloads and objectives onto a single mission, this competition fosters the creation of small spacecraft capable of delivering small payloads to the lunar surface. The GLXP objectives are simple, requiring an imaging and data return package as a payload. The platform designed for GLXP can be used for future science and exploration missions by building a business model that provides science and exploration customers a platform to carry out targeted missions. GLXP is the catalyst for the entry of privately funded development of planetary landers and mobility systems into the space market.

The Next Giant Leap team is developing a Lander/Hopper to win the GLXP. A Lander/Hopper has several advantages over previous planetary mobility systems. Rovers require a landing platform that is discarded after the landing. The Lander/Hopper has both the landing and mobility system integrated onto a single platform. Hoppers are capable of quickly traversing the 500m to win the GLXP and avoid obstacles by flying over them, unlike rovers which have to drive up, around, or through them.

The Lander/Hopper allows a unique capability to land, assess the accuracy of the landing, and quickly hop closer to the desired initial landing target. This concept is referred to as “ultra-precision.” Landing accuracy is no longer

\textsuperscript{11} www.spacex.com/falcon1.php
\textsuperscript{12} www.csaengineering.com/espa/espa.asp
\textsuperscript{13} www.nextgiantleap.com
\textsuperscript{14} www.googlelunarxprize.org/lunar/about-the-prize/rules-and-guidelines
just a function of the landing, but becomes a function of the landing and hopping to achieve the intended landing location. Rovers also have the possibility to increase landing accuracy after landing, but they are usually limited in speed or ultimate roving distance, and may not be able to traverse the terrain between the actual landing location and the intended landing location.

Future NASA missions, like Project Constellation\textsuperscript{15} and the ILN\textsuperscript{2} can use small lander/hoppers to place nodes on the surface to emplace science payloads, act as beacons, site surveyors, or long range triage explorers. The possibilities afforded by such a system are numerous. The small, low-cost approach designed for competing in the GLXP can be expanded to science and exploration missions on the horizon that need dedicated small assets to be precisely placed or spread out over the surface of the Moon.

### III. Mission Architecture

The development and operation of vehicles for planetary exploration have, to date, been done through NASA and other international ventures. The challenges of planetary exploration drove great advances in the cost, size, and performance of space technology. These advances have enabled the development and operation of planetary exploration vehicles by commercial ventures. Small sensors, like the Inertial Stellar Compass\textsuperscript{3} and the use of Micro-Electro-Mechanical systems (MEMs)\textsuperscript{4} reduce mass and power for small spacecraft avionics. Utilizing heritage bus designs reduces system cost and provides a standard platform for the creation of other smaller spacecraft. The Next Giant Leap team is using these heritage pieces to develop a mission architecture to enable landing and hopping on the Moon.

Figure 1 shows the entire stack for the small lunar exploration and delivery system: a Lander/Hopper, Descent Stage, Lunar Orbit Insertion (LOI) Stage, and Trans-Lunar Injection (TLI) Stage. The Descent Stage, LOI Stage, and TLI stage function as propulsion stages only, and get jettisoned once their propellant is expended. As envisaged, the Lander/Hopper will function as the primary guidance, navigation, for the entire mission, from launch pad to end of life, and also function as the main attitude control system (ACS) for the entire stack. The solar arrays, communications, and other avionics are all located on the Lander/Hopper. This simple architecture minimizes the complexity and cost of developing avionics systems for each stage and leaves the main avionics on the payload platform (the Lander/Hopper).

\textsuperscript{15} \url{www.nasa.gov/mission_pages/constellation/main/index.html}
The Lunar Lander/Hopper is designed to be a flexible system, with capabilities that extend beyond automated landing and hopping along the lunar surface. Figure 2 shows the Lander/Hopper. A camera is mounted to the vehicle to gather mission imagery. To communicate and transmit the imagery back to the Earth, a high gain antenna is on a 2-axis gimbal for high-data rate operations, while patch antennas are located on the vehicle for low-data telemetry and contingency operations. The Lander/Hopper utilizes an Orbcomm heritage bus. For maneuverability, there are two types of thrusters located on the vehicle: four vertical thrusters for lunar descent, attitude control, and hover during hopping, and two pairs of thrusters mounted on opposite sides of the vehicle body for attitude control and transverse thrusting during a hop. This simple thruster design allows the vehicle to both land and hop on the lunar surface with the same actuators.
The Descent, LOI, and TLI stages are designed to provide the deltaV needed to reach the moon. The stack is staged to allow jettison of structure after each major burn. The Lander/Hopper remains when all the propulsion stages are jettisoned. Table 1 shows the tradeoff between various trajectories and propulsion stages for emplacing the Lander/Hopper onto the lunar surface. The numbers are based on a study done by Loucks et al\textsuperscript{5}. The Lander/Hopper is sized to carry enough propellant onboard to land the vehicle and continue on for a 500m hop on the surface. A high-Isp fuel with restartable thrusters is required to provide the necessary deltaV to fuel mass ratio to enable the mission design. To reduce cost, all stages use the same propellant and propulsion system architecture.

<table>
<thead>
<tr>
<th></th>
<th>5 Day Transfer to Lunar Parking Orbit</th>
<th>5 Day to Direct Descent</th>
<th>3.5 Phasing Loop to Direct Descent</th>
<th>WSB</th>
<th>$L_1$ Gateway</th>
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<tr>
<td>TOF (days)</td>
<td>5.23</td>
<td>5.03</td>
<td>22.18</td>
<td>90</td>
<td>33.2</td>
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<tr>
<td>TLI</td>
<td>3137</td>
<td>3128</td>
<td>3096</td>
<td>3194</td>
<td>3177</td>
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<td>-</td>
<td>-</td>
<td>41</td>
<td>42</td>
<td>1544</td>
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<tr>
<td>LOI (m/s)</td>
<td>816</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>DOI (m/s)</td>
<td>29</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>22</td>
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<tr>
<td>Staged Braking maneuver (m/s)</td>
<td>N/A</td>
<td>846</td>
<td>832</td>
<td>670</td>
<td>N/A</td>
</tr>
<tr>
<td>Powered Descent (m/s)</td>
<td>1915</td>
<td>2362</td>
<td>2350</td>
<td>2331</td>
<td>1952</td>
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<tr>
<td>S/C DV w/o Descent</td>
<td>845</td>
<td>846</td>
<td>873</td>
<td>712</td>
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<tr>
<td>Total s/c DV</td>
<td>2760</td>
<td>3207</td>
<td>3223</td>
<td>3043</td>
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Table 1. DeltaV trades
New launch options coming into production, like SpaceX’s Falcon 1, 1e, and 9\textsuperscript{16} provide cheaper access to LEO than ever available before. The Falcon 1 provides 420 kg to a 185 km orbit for $7.9M. The Falcon 1e will provide 1010 kg to a 185 km orbit for $9.1M. These launch opportunities will be a huge boost to the utilization of small spacecraft for Earth, lunar, and solar system exploration. Small, cost effective, multipurpose spacecraft capable of carrying small payloads that can land on planetary surfaces, provide mobility, or even the capability to launch back into orbit (off of smaller planetary bodies like asteroids, small moons, etc) will open up new mission possibilities for scientists and explorers.

IV. Mission Description

The lunar exploration and delivery system must travel through many mission phases before finally reaching the lunar surface. The mission architecture is designed to minimize launch costs and deltaV for transfer from LEO to the lunar surface. Figure 3 shows the phases and burns needed to go from Earth to the lunar surface.

A. Launch to Landing

The launch vehicle will insert the stack into LEO at an inclination with the Moon’s plane. The stack will emerge from the launch vehicle fairing and update the navigation estimate of its orbit, point the solar arrays to the sun, and calculate the proper TLI initiation state. At the time of TLI the Lander/Hopper will align the stack for the burn. The TLI burn will impart over 3 km/s of deltaV to send the stack from LEO on a 5-day trajectory to LLO.

After TLI the vehicle will be in the Cruise phase of the mission. The expended TLI stage will be jettisoned and the stack will align to keep the solar arrays pointed at the sun. The remaining stack is the Lander/Hopper, Descent Stage, and LOI stage. Periodic navigation position and velocity updates will come from the Earth in preparation for

\textsuperscript{16} www.spacex.com
LOI. Small trajectory correction maneuvers (TCMs) will be performed as necessary to align the trajectory of the stack for lunar orbit insertion.

Upon approach to the LOI point, the stack will align for the large burn that will put it in a 100 km x 100 km lunar orbit at a 26 degree inclination. During LOI the vehicle will lose contact with Earth ground stations. Once the vehicle is back in view it will once again receive a navigation update from Earth, updating the orbit that was achieved. The expended LOI stage will be jettisoned and the remaining stack (Lander/Hopper and Descent Stage) will make several orbits around the Moon to refine the navigation estimate and align the orbit properly to achieve the landing site.

A small de-orbit burn by the Descent Stage will put the stack into an elliptical 100 km x 15 km transfer orbit. This orbit can be stably maintained for a number of revolutions before drifting too far from over the landing site. This orbit also allows the vehicle time to setup for the final, large descent burn needed to arrest the vehicle’s velocity for a soft touchdown on the lunar surface. The de-orbit burn will occur on the far side of the moon placing the perigee on the near side so that the final descent will land the vehicle in a location optimal for direct transmission of data from the Lander/Hopper back to Earth.

The Descent Stage and Lander/Hopper will perform the final, nearly continuous burns needed to reach the surface, arresting the nearly 2 km/s that will allow the vehicle to touch down softly. During the descent phase the Descent Stage will run out of propellant and be jettisoned. All that will remain will be the Lander/Hopper. The Lander/Hopper will perform a controlled burn to the surface. Once nearly all of the relative horizontal velocity is nulled, the vehicle will pitch-up and descend vertically to the lunar surface.

B. Lunar Surface Operations

Once on the lunar surface, the Lander/Hopper platform can be used for numerous missions. The stationary lander platform can be used for science, technology demonstration, and emplace exploration infrastructure. The same platform used as the hopper opens up many possibilities. The hopper mobility allows the vehicle to travel over the surface faster than rovers and to locations that are not easily accessible by rovers.

In addition, the Lunar Hopper will be able to facilitate science on the lunar surface. The payload capability of a single Hopper is large enough for a small suite of scientific instruments. A single Hopper can be used to place those instruments at pre-determined locations interesting for surface operations and science. Once on the lunar surface, the Hopper has minimal maintenance and ground operation requirements, keeping costs down, and allowing the bulk of the communications and processing bandwidth to be dedicated to science. For larger projects, a team or teams of cooperating Hoppers can be used to create a large sensor array. Each Hopper will be capable of relocation through multiple smaller hops, or one large hop. Science missions, like the proposed International Lunar Network (ILN), will emplace at least 4 nodes on the lunar surface to gather data on the lunar environment thru seismology, electromagnetic, thermal, and ranging experiments. The cost of current lander missions, for a single NASA-funded lander, is in the hundreds of millions of dollars. A simple, cost effective, method to provide nodes for ILN science is key to the success of such missions.

The Lunar Hopper can also support NASA’s Exploration program, which includes one of the largest lunar initiatives in the near future. NASA intends to develop a suite of missions that will culminate with a permanent manned base located at the Moon’s South Pole. These missions provide a significant opportunity for a Lander/Hopper to play multiple roles in the exploration and development of the lunar surface. One of the issues that the Exploration program will face is the lack of infrastructure on the Moon. Hoppers can be emplaced as a network of navigation beacons or communication stations, establishing the necessary infrastructure to allow astronauts or autonomous vehicles to explore large areas of the lunar surface without needing to carry the extra equipment that would be needed in an undeveloped area. Hoppers can also be used to survey areas of interest on the surface, either through remote sensing from orbit or from inspection of multiple sites by a landed vehicle. This can be done to generate more accurate maps of the surface, or to search for resources that would be useful for explorers.

Hoppers can also perform sample return missions to locations on the lunar surface too dangerous for astronauts or difficult for rovers. Hoppers can hop to the bottom of craters, retrieve samples, and return them out of the crater for astronauts to retrieve or to a base station for return of the samples back to lunar orbit and eventually back to Earth.

There will be many new technologies that will need to be developed for the exploration of the solar system, and the Moon provides a nearby location that exhibits many properties of other celestial bodies in the solar system. A cost effective platform, such as the simple Lander/Hopper concept, allows for these technologies to be tested in a relevant environment much cheaper than typical missions. Any mission to another planet, moon, asteroid, comet, etc, will have large risk, cost and development time associated with it. By testing new technologies in a local yet similar area, those risks can be reduced. The Hopper can be used to test landing technologies, attitude determination

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technologies, power generation and storage technologies, scientific sensor technology, material technology, and communications technology, to name a few. This can be done as a sub-mission to a larger Hopper mission (such as testing a new landing guidance system by having it run in parallel to the main Hopper system, but without control of effectors for a NASA sponsored resupply mission), or by having a dedicated Hopper mission exclusively for testing out the new systems.

V. Conclusion

The future of space exploration will come from a strong partnership between the public and private sector, with the use of new technologies and platforms to fulfill the growing needs of exploration, science, and commercial interests. The Next Giant Leap concept embraces the new paradigm and creates a unique and promising solution to the growing needs for missions to the Moon and beyond.

The Lander/Hopper mission architecture has several advantages over other forms of planetary exploration and science platforms. The Lander/Hopper is both the landing and mobility platform, eliminating the need for having two vehicles by combining the functionality onto one. The Lander/Hopper uses rocket propulsion for mobility. This provides the ability to quickly move from the initial landing location to a new location to increase landing precision, termed “ultra-precision.” Hoppers can also go places that conventional rovers have not been able to go, by flying over obstacles too tall to climb or traversing down craters and rilles that are too steep for roving.

This type of mission architecture utilizes a cheap, expandable method to send small payloads around the solar system. With the onset of new launch capabilities, heritage small avionics, and innovative design, scientists and explorers will be able send more payloads to space to discover and pave the way for future science and exploration.

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