IAC-19,A3,IP,7,x52520

The USC ADAM Project: Advanced Developmental Architectures for Our Moon

Madhu Thangavelu[a]*, Duy Nguyen[b], Ivan Figueroa[c], Danielle Waters[d] Martin Greco[e], Caitlyn Alexander[f], Zachery Bates[g], Jeffrey Asher[h], Alexander Sullivan[i], Robert Antypas[j]

[a] *Conductor, ASTE527 Graduate Space Concept Synthesis Studio, Department of Astronautical Engineering, Viterbi School of Engineering, Rapp Research Building, & the School of Architecture, University of Southern California, University Park, Los Angeles, California 90089-1191. mthangav@usc.edu*
[b-j] *Graduate Student, Department of Astronautical Engineering, Viterbi School of Engineering, University of Southern California, Rapp Research Building, University Park, Los Angeles, California 90089-1191.*
* Corresponding Author

"Lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations;". – White House Space Policy Directive #1

Abstract

The US administration has laid out, in the clearest terms yet in many years, what the nation expects NASA to do in the immediate term: Return people to the Moon asap(2020s timeframe) with the goal of building the technological and operational infrastructure to conduct a safe human Mars expedition within the next two decades(2030s).

A fresh new space policy outlook drives an invigorated agency impetus to incorporate homegrown private space companies, that are chomping at the bit with creativity and new visions for utilizing human spaceflight for commerce and profit, and NASA is already showing signs of nurturing many more partners, both commercial and international entities into the core of this vital civilian endeavor, particularly in human space activity.

How to jumpstart a self-sustainable cislunar economy that does not wither and fade with each administration cycle and be victim yet again to the on- again off-again visions for human space activity ?

Robotic precursor missions to both Moon and Mars have been underway for some years now, with the aim of gauging in-situ resources for extended human activities, eventually leading to permanent settlements. Following the Apollo missions nearly half a century ago, several reports have presented the case that the Moon is the most proximal celestial body where much of the hard engineering data and experience needed for more ambitious missions may be tested, evolved and certified.

Commerce is the lifeblood of modern civilization. Commerce is a pillar of national security. Open-ended government funded space exploration, by itself, is not sustainable for future long duration missions. Hence the role of commerce and international partners in human space activity. An effort to expand the International Space Station model to include more partners on a global scale is also proceeding in parallel.

The goal to develop and field the next generation of human occupied space station, one that can safely keep her crew and reliably operate beyond the protective cocoon of the Earth's magnetic field is logically the next step along the critical path for evolving a Mars expedition vehicle, one that has to withstand the interplanetary environment, before crew can be delivered to the surface of Mars.

While large, heavy lift launch vehicles and planetary landers are being developed, integrated and tested, are there ways to speed up human spaceflight activity ? What projects can we do with existing human spaceflight assets that are aligned with administration space policy directives ? The ADAM Project attempts to explore options available in the immediate term, to satisfy the national space policy goals set forth by the current administration, while encouraging new visions for human space activity, utilizing existing space technology to accelerate real space commerce for the immediate benefit of all society.

The USC 2018 ADAM Project continues in a long line of past lunar projects that make the case for speedy lunar return. The ADAM project concepts and earlier works of the ASTE527 Studio may be accessed at : https://sites.google.com/a/usc.edu/aste527/home

The current US administration White House directives, the ISS Transition Report and the National Space Exploration Campaign Report were helpful in shaping the Adam Project concept synopses that are presented.

Keywords: Return to the Moon, White House Policy SPD#1, Mars Forward Agenda, Gateway Project, Commerce

1. Introduction

"Lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations;". – White House Space Policy Directive #1

The US administration has laid out, in the clearest terms yet in many years, what the nation expects NASA to do in the immediate term: Return people to the Moon asap(2020s timeframe) with the goal of building the technological and operational infrastructure to conduct a safe human Mars expedition within the next two decades(2030s).

A fresh new space policy outlook drives an invigorated agency impetus to incorporate home grown private space companies, that are chomping at the bit with creativity and new visions for utilizing human spaceflight for commerce and profit, and NASA is already showing signs of nurturing many more commercial entities into the core of this vital national endeavour, so the United States can continue to be preeminent in spaceflight, particularly in human space activity.

Barely had word got out, and enthusiastic debates are already raging about how to go about unpacking this directive, and whether we should go to lunar orbit or directly to the Moon first. Why are we going to the Moon, if we are not landing on the Moon ? How to jumpstart a self-sustainable cis-lunar economy that does not wither and fade with each administration cycle and be victim yet again to the on- again off-again visions for human space activity that past administrations have proposed ?

One of the prime functions of systems architecting is to resolve such conflicts using synergies that are not apparent at first sight. Indeed, the national space policy does offer solutions to all those questions and more. Subsequent documents including SPD-2 and SPD-3 along with the ISS Transition Report and the National Space Exploration Campaign Report offer some clues on how to go about realizing the vision laid out in SPD-1, the first directive.

If we follow the space policy agenda laid out by the current administration, the essential human spacecraft architectural elements needed to achieve this goal for lunar return with a Mars Forward vision quickly and safely include:

1. A safe launch system from Earth to an orbit that various nations, commercial space companies and their launch systems can access using proven hardware, both for crew and cargo,
2. A sturdy interplanetary transit vehicle for the crew to go to Mars and back, one that can protect the crew and systems from the unknown effects of interplanetary and solar weather(Galactic Cosmic Radiation and solar particle radiation) especially on crew during long transit period,
3. A reliable planetary lander that can safely land and put the crew on transit back to Earth,
4. A dependable atmospheric entry craft for returning the crew safely back to Earth.
5. And most important, a reliable communication system that can keep the crew and mission control in contact throughout the course of the expedition.

Many of the elements listed above are in various stages of development, some yet to start, and NASA is training both government and commercial crew for missions to the ISS in LEO and beyond.

Note that ISS is a Low Earth Orbiting space station. An interplanetary vehicle, especially during the long transit period, will have very different characteristics while operating in interplanetary space. For instance, the vehicle will not have the same thermal cycling profile, since the spacecraft attitude along the trajectory is different. Hence the power system optimization is different. The systems and configuration are affected by deep space radiation as well, to name a few. A new set of engineering requirements will follow in the design of such interplanetary spacecraft, to be evolved, tested and certified before such an expedition is commissioned.

Robotic precursor missions to both Moon and Mars have been underway for some years now, with the aim of gauging in-situ resources for extended human activities, eventually leading to permanent settlements. Following the Apollo missions nearly half a century ago, several reports have presented the case that the Moon is the most proximal celestial body where much of the hard engineering data and experience needed for more ambitious missions may be tested, evolved and certified.

NASA holds global mystique. NASA has agreements with more than 130 nations to conduct joint missions and space experiments, much more than any other nation has in any complex international endeavour to date. Several robotic spacecraft, many carrying components and equipment developed by international partners are expanding the frontiers of knowledge, from detecting water on our Moon and monitoring Climate Change on Earth, attempting to measure the pulse of Mars, to studying our sun at close range. Some spacecraft are even racing beyond the domain of our solar system. Other missions are currently peering out to gauge the depths of our vast universe, unravelling the mysteries of our Cosmos and our origins and future prospects for our home planet and our species while searching for others.

This alone should prove US pre-eminence in space activity, not to mention the ISS is the only permanently occupied human crewed orbiting facility that is approaching an unparalleled two decades of continuous operations. Needless to say, NASA folks have their hands full, and is welcoming new partners to begin human missions beyond low Earth orbit.

Commerce is the lifeblood of modern civilization. Commerce is a pillar of national security. Open-ended, taxpayer funded space exploration, by itself, is not sustainable for future long duration missions. Hence the role of commerce and international partners in human space activity. An effort to expand the International Space Station model to include more partners on a global scale is also proceeding in parallel.

The goal to develop and field the next generation of human occupied space station, one that can safely keep her crew and reliably operate beyond the protective cocoon of the Earth's magnetic field is logically the next step along the critical path for evolving a Mars expedition vehicle, one that has to weather the interplanetary environment, before crew can be safely delivered to the surface of Mars.

While large, heavy lift launch vehicles and planetary landers are being developed, integrated and tested, are there ways to speed up human spaceflight activity? What projects can we do with existing human spaceflight assets that are aligned with administration space policy directives? The ADAM Project attempts to explore options available in the immediate term, to satisfy the national space policy goals set forth by the current administration, while encouraging new visions for human space activity, utilizing existing space technology to accelerate real space commerce for the immediate benefit of all society.

The USC 2018 ADAM Project continues in a long line of past lunar projects that make the case for speedy lunar return. Earlier projects may be accessed at : https://sites.google.com/a/usc.edu/aste527/homeThe White House directives, the ISS Transition Report and the National Space Exploration Campaign Report were helpful in shaping the Adam Project that is presented.

The following sections 2-10 are synopses of various concepts presented by graduate students in the ASTE527 Space Concepts Studio on December 11th, 2018, the first anniversary of the signing for the Space Policy Directive #1 on December 11, 2017 by the president of the United States of America.

2. Modular Assembly of A Lunar Orbiting Station in Low Earth Orbit(LOS-MALEO)

In 2017, per Space Policy Directive-1, NASA has now refocused agency efforts on returning to the Moon. The current plan calls for the construction of a Lunar Orbiting Station (LOS) in 2022, with support from commercial and international partners. LOS will lay a technological and logistical foundation that will eventually enable human expeditions to, and exploration of Mars and beyond.

The proposed concept architecture provides an option to achieve such a goal within the given timeline by using existing and mature technologies and infrastructure of various national space agencies and private industries, and incorporating lessons learned during ISS development and commission. This strategy would allow many new and emerging spacefaring nations to take an active, collaborative role in sharing resources for a quick

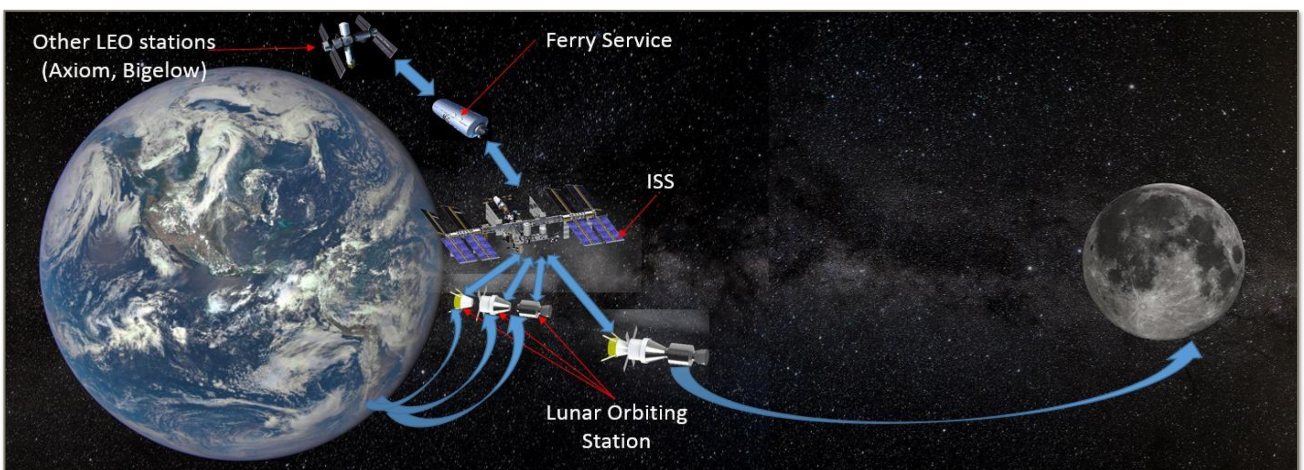

Figure 1. The International Space Station (ISS), which was originally conceived to be "an assembly capability from which large space structures and systems are assembled and verified", will provide a valuable platform to build and test the LOS in LEO, even though the facility might not be in the ideal location for supporting lunar missions. Eventually, Mars expedition vehicles may also be assembled at certified for missions in suitable orbits in LEO.

and sustainable return to the Moon, setting the stage for more ambitious expeditions to Mars and beyond.

As space exploration advances, so does the need for heavier payloads. Scaling up launch vehicles to take on heavier payloads has proven to be difficult and costly. Therefore, it is less risky and more economical to launch heavy payloads in smaller, modular segments. Small, low-cost, and reliable stable of rockets, currently available in the international arena and within the private sector, can be used to bring those small segments up to space and assemble there, preferably in Low Earth Orbit (LEO).

The International Space Station (ISS), which was originally conceived to be "an assembly capability from which large space structures and systems are assembled and verified", will provide a valuable platform to build and test the LOS in LEO. The experience and expertise of ISS astronauts along with state-of-the-art telerobotic agents can significantly reduce cost, risk, and schedule during assembly and test operations.

Once completed, a translunar injection can be performed to bring LOS to its destination. In addition, as the ISS was projected to offer "a servicing capability from which payloads and vehicles are maintained, repaired, replenished and refurbished", it can also be used as a service center for other future LEO stations, providing valuable cooperation opportunities between NASA, international agencies, and private entities.

Given the current schedule, the LOS-LEO proposal presents the case that the best strategy to meet Space Policy Directive-1 vision in a cost effective and timely manner is to assemble the LOS in LEO, employing a modular strategy, using as much current technology and infrastructure as possible, including the experience gained by ISS assembly and commission and her crew. This is a reliable, low-cost, and low-risk approach that still has the potential to be scaled up for much larger and more ambitious missions, including construction and commission of an interplanetary Mars Expedition Vehicle. [See Figure 1.]

3. OCTANE: A LEO Fuel Cache-Tanker

A paradigm shift is currently underway in terms of the commercialization of space. For in the first time since the dawn of the space age, space travel is no longer the exclusive domain of governments. The last few years have seen a proliferation of private space companies that are racing to fill and create markets near Earth and in cislunar space. However, as with government-backed efforts, a good deal of progress is being hampered by the fact that any fuel used to operate beyond orbit must be carried along all the way from the Earth's surface. This severely limits the range of movement of spacecraft and constrains the ability to conduct missions on a large scale. A possible solution to this limitation and one way to circumvent the laws of physics is to place the fuel in orbit.

Orbit-based fuel depots are not a new idea in the realm of space mission architectures. For there have been many proposals for the storage and distribution of rocket fuels in space. However, the focus of many of these proposals have been to either make commercial applications secondary in nature, as in the proposed use for NASA Near-Earth exploration missions, or are relegated to very long-term development timelines, such as large fuel stations that produce and store fuels.

There is a niche market for near-term fuel access within the next half a dozen years that is being overlooked. An intermediate solution may be viable. OCTANE is intended to fill this market gap and serve as an interim step between now and the future deployment of large scale fuel depot facilities. How OCTANE proposes to go about achieving this is through the use of short term fuel caching. [Figure 2]

Figure 2. Analogous to gas stations on Earth, short term fuel caching would allow refueling capabilities in the near term

It will try to take advantage of many existing technologies such as storable hypergolic fuels, and an initial, simple design that aims to incorporate existing hardware and strive towards a modular, plug-and-play mode of usage. The design will need to mature with time to incorporate technologies such as fuel transfer and modular assembly in order to extend range of operations and compete with more efficient fuel types. With an emphasis to capture market share, initial operations will be well within earth's orbital regime in roles such as: satellite servicing, on-demand orbit transfer/plane changes, orbital debris mitigation and station keeping. From this point, with the concurrent development of fuel depot technologies, it can be expanded to support the operations in cis-lunar space such as the Lunar gateway, EM-L1, or lunar surface missions. Further studies, detailed trades, and investigation of the OCTANE concept is warranted.

4. Architecture for Radiation Testing at Earth-Moon L1 Station (ARTEM1S)

Space Stations require long-term investments of both time and money from multiple collaborating nations and must therefore be designed with the future in mind. Commercial and government agencies are rapidly developing technologies to make what was once only possible in sci-fi into reality, and it's time to start putting their creations to the test. The next generation space station must be used as a proving ground for critical deep-space technologies. In addition, it should provide access and support for near-term lunar missions as well as long-term Martian missions.

The ARTEMIS concept proposal will explain why NASA's current plan for an incrementally-built lunar space station in a Near-Rectilinear Halo Orbit around the Moon is not the optimum approach to creating a human presence beyond LEO. Instead, the optimal location for the ARTEMIS lunar station is between the Earth and the Moon at Lagrange Point 1. The L1 location has almost no restrictions on when or how often it can be accessed from either the Moon or Earth and can be in constant communication with both. By using two Bigelow B330 expandable modules as the core of the station, it can be assembled in LEO and pushed out to L1 very soon, up to 12 passengers can stay at a time, and a universal docking port design will allow multiple government and commercial companies to ferry astronauts and tourists between the ISS and ARTEMIS at L1S. It can operate as a test-bed for nuclear-fission reactors, such as Kilopower, which will be necessary for long-term lunar bases that will see 14 days of constant shadow during a moon "night" and for missions to Mars since solar power is inversely related to the square of the distance from the sun. Most importantly, NASA can study the effects of deep space and solar particle radiation incident from all angles, providing a high fidelity simulation environment. The hard data would be used to determine the threat to crew and develop countermeasures to shield crew and living matter like plants from their deadly effects over a prolonged period of time, comparable to interplanetary transit. Current technologies are insufficient to protect humans from highly damaging Galactic Cosmic Radiation, which has forced us to limit our space exploration to orbits just above the atmosphere inside the relative safety of the Earth's Magnetosphere. Innovations such as using water and fuel as a shield between space and crew (near-term) and creating a portable pseudo-magnetosphere using plasma and electromagnets (long-term) need a proving-ground that effectively mimics the level of exposure on the Lunar surface and especially during transit to Mars. The utility of an in-situ test ground for developing technologies that have applications above Low-Earth Orbit cannot be overstated, and L1 is the ideal location for such activities.

Stepping out further into space is a vast undertaking that will require collaboration to push-boundaries and achieve lofty goals. It is short-sighted for NASA to create a lunar station that serves only the purpose of exploring the Moon when humans are so close to taking that next step out into the Solar system. It is time to expand our knowledge, put new technologies to the test, and push the future of human spaceflight to the Moon and beyond.[Figure 3]

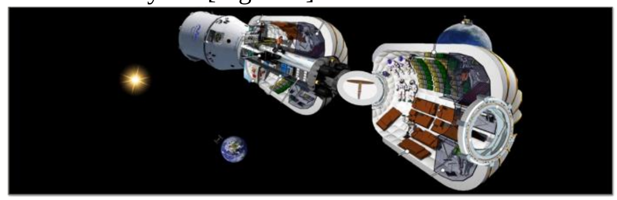

Figure 3. Deep Space Radiation tests may be conducted at ARTEMIS at the Earth-Moon L1 point

5. Lunar Prospector ElectroMagnetic Rover for Sample Return (LEMURS)

Lunar samples have provided a wealth of information on planetary formation. All Apollo lunar samples to date have been recovered by manned missions, resulting in samples from six locations. Increasing the diversity of samples from various lunar sites could lead to further insight into the evolution of the solar system and also how the Moon and planets are formed. Since the Moon has been geologically dormant for long, careful sampling from specific regions may also help us to learn more about solar activity over geologic time. Since the termination of the Apollo and Lunar programs, no new lunar samples have been brought back in almost five decades. Currently, several nations are planning robotic lunar sample return missions.

A lunar orbiting station is being planned with orbit-to-surface tele-robotics as a prime technology that is integral to this facility as well as a critical architectural element for future planetary exploration vehicles. The proposed lunar polar orbit would allow this station to closely examine wide swaths of lunar terrain for detailed investigation of resources and potential landing and settlement sites in advance of deploying landers and vehicles to explore and eventually develop lunar surface infrastructure.

A concept architecture proposal is presented for a Lunar Prospector & Sample Return Rover that can be operated autonomously, telerobotically, or in-situ. The proposed rover will launch lunar encapsulated samples to be retrieved by an existing Lunar Station that is in low-lunar orbit through propellant-less means. The reusable, propellant-less concept for lunar sample retrieval will extend the range and operational life of the sample rover.

Using a telerobotically operated mobile system to pick up samples from the surface, small sample specimens from various regions are encapsulated and launched to low lunar orbit where it is captured and retrieved by an electric propulsion-based chaser system. After rendezvous and capture, the sample capsule is delivered to the orbiting station for study or for return to Earth. The chaser system architecture is part of this concept but not detailed in this presentation. It is planned for future studies.

A roving sample return platform would be capable of returning a variety of samples from different regions of the Moon. Such a Lunar Prospector & Sample Return Rover system architecture can provide an augmented lunar prospecting and sample return capability by involving industry that is already working on key technologies that would be required for such a program to be feasible. .[Figure 4]

The capability to augment the prospecting rover into a mining system is discussed.

and medical supplies, as well as spare parts and vital redundant hardware are all good candidates for caching.

The APPLES architecture proposes utilization of existing assets like low cost launch vehicles as well as state-of-the-art commercial developments in lunar landers. By splitting up supply missions to send ahead of their need, smaller and more cost-effective commercial launch vehicles can be used. Excess capacity on launchers and missions to various orbits and destinations could also be used to deliver and aggregate caches, bolstering strategic logistics in cislunar space and on the Moon and beyond.

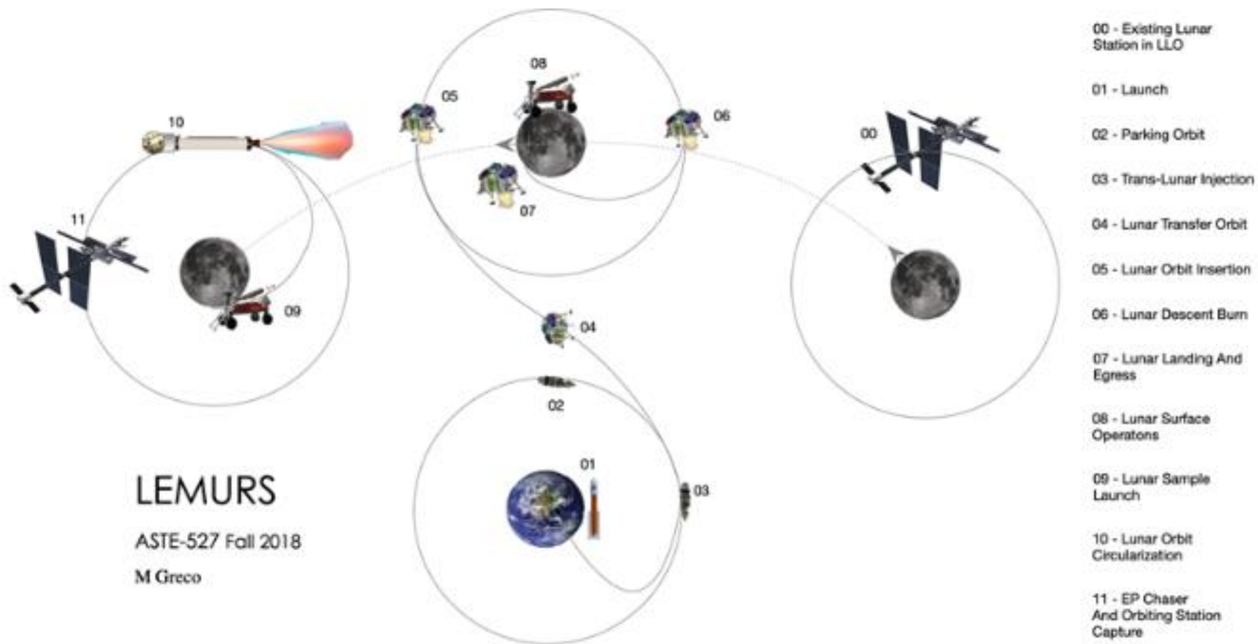

Figure 4. LEMURS concept proposes electromagnetic propellant-less launch of lunar samples and electric propulsion assisted sample capture and rendezvous system for prospecting from lunar orbiting station(Gateway)

6. Architecture for PrePositioning Lunar Expedition Supplies (APPLES) Strategic Logistics for Human Space Activity

Supply caching has been utilized by humans and animals throughout history in order to save for unexpected needs and carry out complex tasks. It involves prepositioning supplies and spare equipment in strategic locations for retrieval and later use. This strategy has been widely applied in military ground operations, especially in scouting missions and forward operating base procedures. When applied to strategic logistics in cislunar space missions, caching can greatly improve and enable mission architecture while lowering costs, extending range of operations, allowing for adaptation to new mission requirements, and enhancing safety of crew and equipment.

Fuel and supplies can be cached in various locations, such as low Earth orbit, lunar orbit, and on the lunar surface. Consumables, such as fuel, food, water,

Caching also allows for staging longer duration missions by providing fuel and other supplies precisely where they are needed to continue the next leg of the mission. This is especially useful for refueling after launch and can also be applied to lunar surface exploration to expand the mission range.

Mission safety to both crew and equipment is also improved by caching. By placing critical supplies in close proximity, emergencies can be addressed quickly. This also allows for flexibility to adapt to new mission requirements.

Supply caching, which can be done with existing hardware, will greatly reduce cost, advance logistics, and improve safety for immediate and near-term lunar missions and further enable humans to reach the Moon by 2022. Furthermore, caching could play a vital role in accelerating the Mars Forward vision laid out by the administration.[Figure 5]

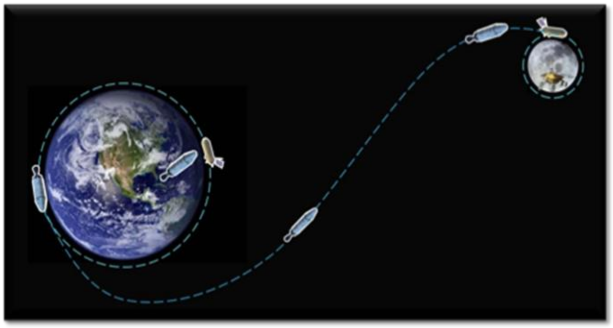

Figure 5. Strategic Caching can lower costs and extend mission range and also enhance crew safety

7. Lunar Lava Tube Exploration (LuTE)

Underground cavities formed by molten lava flows after volcanic eruptions are called lava tubes. Lava tubes are common geological features on planetary bodies that are formed by volcanism. Past proposals have pointed to using such structures for habitation but also noted the difficulty to access them.

Recent high-resolution imagery of the Moon and Mars continue to detect terrain formations like pits, bridges, cave-like structures and breaches in what appear to be lava tubes. The lunar surface features over 200 skylights, which could present access points to such lunar lava tubes. These skylights and lava tubes could provide great scientific returns, might hold resources, and perhaps provide natural habitable space for human settlements and other underground networks and applications including logistics, all sheltered from the harsh lunar environment.

While proposals have been made to explore lunar lava tubes, currently, there are no missions scheduled to explore lunar skylights or lava tube interiors, largely due to the uncertainty of a profitable exploration.

The LuTE concept architecture presentation focuses on the concept of low cost planetary exploration probes that can piggy back on other exploratory lunar missions. These probes would act as initial scouting missions of potential skylight and lava tube structures, allowing for the determination of whether the structure is worth a dedicated robotic mission, followed by human exploration. These probes and their architectures, once established, could be extended to explore the many planetary features including Martian skylights and associated lava tube systems.

Since the Moon is the closest celestial body to Earth, orbiting just a quarter million miles away, it may be possible to conduct the first robotic lunar lava tube exploration mission from Earth, followed by telerobotic controlled missions from a lunar orbiting station. If such precursory activity points to promising data, then detailed exploration could be undertaken by more sophisticated means including astronaut assisted exploration of lunar lava tubes, eventually leading to establishing permanent lunar lava tube settlements.[Figure 6]

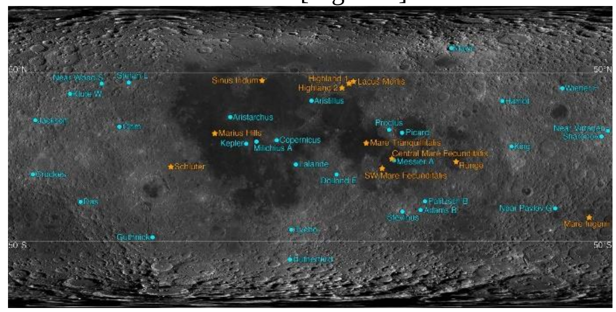

Figure 6. Recent discovery of roof breaches called "skylights" would allow exploration of lunar lava tubes

8. EVE: Rapid Orbit to Surface EVA for Repair and Anomaly Resolution

This concept prioritizes potential commercial services provided by the proposed Lunar Orbital Gateway to spur commercial development of cislunar space, acting as a beneficial piece of infrastructure, while also informing future Mars missions. The commercial development of the lunar surface is dependent upon the sustainable operation of a fleet of robotic surface assets to cooperatively extract, refine, and transport resources. Landers, launchers, resource extractors, prospectors, movers and manipulators are all examples of the different robotic lunar surface assets needed to develop an end-to-end lunar economy.

This concept proposes utilizing the Lunar Gateway to provide key services including low-latency teleoperations, and responsive manned orbit-to-surface sorties for anomaly resolution and repair. This concept concludes that a Lunar Gateway in Low Lunar Orbit (LLO) is beneficial to provide such services. This concept architecture relating to the Lunar Gateway allows for extensions of recently executed telerobotic experiments on the International Space Station (ISS)[1]. A reference telerobotic mission including astronaut assistance is presented.

Short duration anomaly resolution and repair sorties provides a valuable service for surface assets and operators while pushing towards national objectives of a manned return to the Moon[2]. These short duration sorties would leverage the gateway as a dispatch post with global reach, small commercial unpressurized landers[3], and heritage hardsuits[4] to ensure rapid response. The quick response and in situ presence of astronauts has the potential to drastically decrease system downtime due to anomaly resolution, which is typically executed remotely. These maintenance sorties provide an opportunity to train for future global exploration campaigns on Mars while also prioritizing sustainable robotic operations on the surface. The capstone of this concept is the deployment of a surface repair facility. This facility provides generic support for mechanical and electrical failures and an air purge system to clean the rover surface of harmful lunar dust, preventing premature loss of mission. In addition, the repair facility serves as a local command, control and communications (C3) hub for surrounding assets. This deployment will target landing sites populated with a variety of robots and rovers delivered in the early-to-mid 2020's, delivering critical capability and providing a path forward for future commercial handover. [Figure 7]

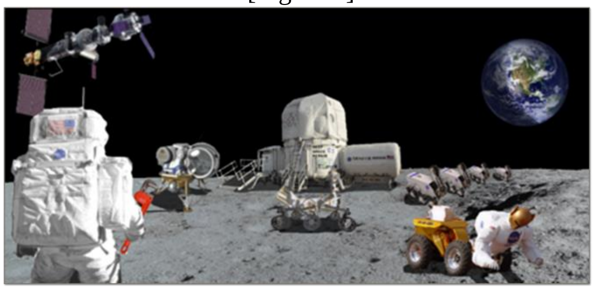

Figure 7. A lunar orbiting station(Gateway)can support prompt lunar surface operations anomaly resolution across the globe by deploying crew from orbit as and when needed. This is a vital technology for future planetary exploration

9. EDEN: Extraterrestrial Distributed Ecoculture Network

Astronaut crew will need ample supplies for the long Mars expedition which will take at least six months of one-way transit in interplanetary space. Crews on the International Space Station are currently fed dehydrated Earth food which is produced and delivered to Low Earth Orbit on a periodic basis for an enormous cost of around $72,000/kg. Extended human presence in cislunar space, on the lunar surface and en route to Mars will simply not be sustainable on finite rations from Earth resupply. In contrast, the Moon is the closest, largest geocentric satellite with enormous solar potential and vast, natural, pristine surface available for extraterrestrial farming. And at 1/6th the gravity well of Earth, the Moon affords tempting, sustainable cost advantages for crop cultivation and transportation of fresh food from the lunar surface into both cislunar orbit and even to LEO at a lesser delta-V than traditional Earth-based resupply. Therefore space architectures which enable lunar agriculture offer an attractive option to realizing a self-sustaining, space-faring society.

In this proposed Extraterrestrial Distributed Ecoculture Network (EDEN) architecture, the feasibility of lunar surface agriculture to sustain human presence on the lunar surface and in lunar orbit is considered in context of NASA's current Lunar Exploration Campaign Roadmap.

A long-term vision is presented depicting the engineering of a crop cycle on the lunar surface by staggering lunar greenhouse modules across lunarlongitudes following natural diurnal lunar cycle. The architecture is evolved in phases, and enabling technologies for the Phase 1 design are considered. A detailed design for Phase 1 of the architecture is presented in the form of a remote demonstration of a mobile greenhouse spacecraft ready by 2022. The critical deliverable of the design is a versatile, reusable lunar ascent/descent utility lander capable of sub-orbital hops and injection into Low Lunar Orbit, where it may rendezvous with NASA's Lunar Orbiting Gateway. Finally, associated challenges to the architecture are assessed, and future works are itemized for subsequent phases of the mission architecture.[Figure 8]

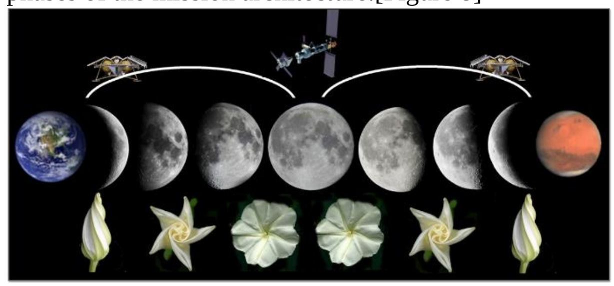

Figure 8. Using augmented lunar resources and following the lunar day/night cycle to produce fresh food for crew would be a critical step in developing a truly efficient spacefaring capability for humanity.

10. Sustainable Enterprise Roadmap for Profitability Employing Nascent Tourism (SERPENT)

Reusable launch systems have forever changed the cost of Earth-to-Orbit space access. The operational Spacex Falcon series of rockets and current vehicles in development at Virgin Galactic, Blue Origin and StratoLaunch have proven that the age of expendable launchers is fast coming to an end. [Figure 9]. This has resulted in the burgeoning space tourism industry that is on the precipice of transforming the way humans utilize the vast unknown frontiers all around us. From the first commercial space tourist, Dennis Tito, to the two hundred thousand that signed up for a one-way trip to Mars with Mars One, the space tourism business is ripe with eager customers. These customers should be able to experience what the current space age has to offer while funding the capital necessary to build the future and explore further and faster. [Figure 9,10]

Building on past tourist missions to the Mir and ISS, as well as the current log on Virgin Galactic and Blue Origin among others, this proposal sees a near term opportunity to extend space tourism into the cislunar domain. The MOBIUS concept proposes such an architecture.[Figure 11]

Figure 9. Reusable launch systems like the Spacex Falcon series have forever changed the cost of Earth to Orbit transportation.

Reusable launch vehicles and transatmospheric spacecraft like the STS and the Dreamchaser currently in development have changed the "access to space" paradigm forever.

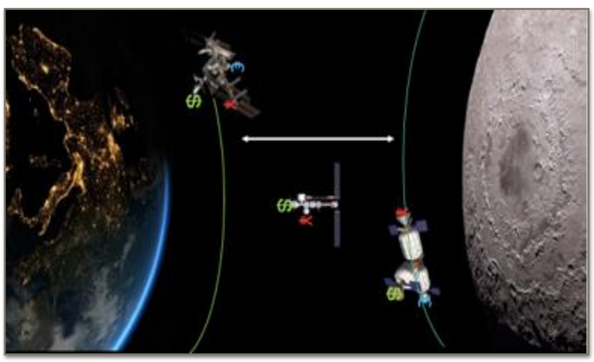

Figure 10. From Earth orbit to lunar orbit, space tourism is the low-hanging fruit that is ready to jumpstart a truly spacefaring economy

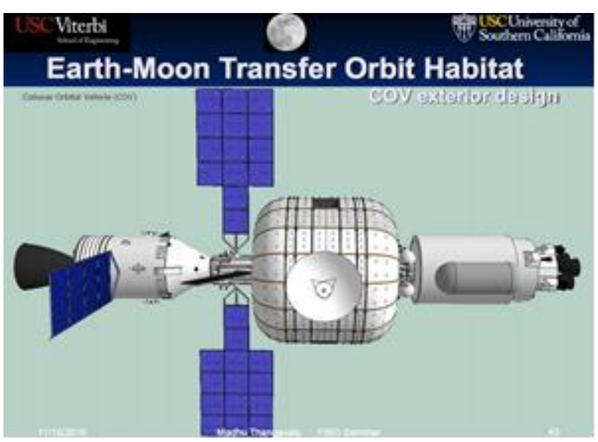

Figure 11. The MOBIUS architecture proposes mostly existing space systems and employs supersynchronous orbits to bring tourists on close approaches to the Moon.

Using existing and maturing assets, including fully reusable rockets that have drastically reduced the cost of access to space, this concept architecture attempts to create and operate a self-sustaining model, that could evolve gradually from lunar orbital missions to landing and lunar surface excursions.

As the rate of space tourism picks up, data collected on human physiology and human factors can greatly enhance and accelerate space technologies needed for much more ambitious missions. Such activity could spearhead a revolution in rapid "rocketset" global transport of people and cargo to anywhere in the world in less than half an hour !

Space no longer belongs solely to NASA and the handful of other government agencies around the globe that have fully funded and subsidized open-ended human space exploration till now. While NASA has led the way by spending billions on research and advancement of knowledge, the future lies with corporations reaping trillions of dollars in economic gain. Space will be capitalized by corporations like Blue Origin, SpaceX, Virgin, Bigelow, Stratolaunch and hundreds of smaller organizations. These organizations are willing to spend billions of dollars of capital to tap the potential reservoir of trillions in human hopes and dreams. People have lined up and paid upwards of $50M just to see and experience space. More will que when the price drops and the experiences blossom into a wealth of long duration adventures. The first few high net worth customers from around the world to take the leap into the unknown and orbit the Moon will bring much needed capital that can accelerate current agency plans to reach the Moon by 2024.

11. ADAM Project Recommendations

1.Follow US Administration Policy

The space policy set forth by the current administration and the supporting bodies established to guide NASA, including the National Space Council and NASA Advisory Council, offers the best path yet to make humanity a truly spacefaring species: Return humans to the Moon and Mars quickly, in a practical, speedy and economic manner.

2. Build Lunar Orbiting Station(Gateway)

The goal of establishing a Lunar Orbiting Station(Gateway) is clearly aligned with the current space policy and is logically the right mission and engineering program, ahead of any lunar landing mission.

3. Speedy Buildup in Low Earth Orbit

Given the complexity of assembly involved, and the number of private and international partners involved, Gateway may be speedily built and commissioned in Low Earth Orbit.

4.Build and Test and Certify Lunar Orbiting Station(Gateway) at or near ISS

Though not ideally located for frequent lunar access, the ISS offers a practically useful platform from where to supervise, help assemble and certify the safety of lunar orbiting station(Gateway), using existing assets, vehicles, ISS crew and proximal Earth mission control.

5.Versatile Upper Stage Needed for TLI – Full Reusability preferred

A versatile and capable and fully resuable upper stage is needed for trans lunar injection(TLI) of the lunar orbiting station(Gateway) from ISS. If a reusable upper stage can be serviced and refueled in LEO, it would make cislunar missions routine, after the initial buildup of lunar orbiting station(Gateway).

6. Strategic Logistics and Caching

Prepositioning of consumables including fuel, spares and vital redundant hardware and supplies can improve mission performance, especially during exploration missions with open-ended approach, enhancing the ability to tailor the mission as it proceeds in real time.

7. Lunar Orbiting Station(Gateway) - Raison d'etre – Deep Space Radiation

Radiation kills. Practicing doctors and radiation medicine professionals know exactly how the body deteriorates from, and succumbs to, radiation exposure. NASA Astronaut Office keeps careful check on crew dosage for all missions. We cannot let radiation affect the safety of brave astronaut crew. We need to protect our crew from the beginning to end of mission tour of duty. We do not have any hard data effects of deep space radiation on living tissue.

The primary and critical mission of this lunar orbiting station(Gateway) is to study the effects of deep space environment, especially deep space radiation(GCR) and anomalously large solar particle events(ALSPE) on live biological tissue. Animals and plants are to be exposed first, and parallel development and test of countermeasures, as needed, will then lead to development and test of countermeasures as needed(if needed) to safely sustain human crew physiology, and for evolving sturdy crewed spacecraft systems for mission to Mars, especially during interplanetary transit.

Since design and engineering experience and hard data is currently limited to short Apollo missions and Low Earth Orbital stations, this deep space radiation data is deemed critical to develop, evolve and certify a safe Mars Transit Vehicle architecture. No crew safety certified interplanetary transit vehicle(IPTV) = No Mars mission. This technology development and certification is along the critical path for Mars Forward vision. IPTV operational environment, especially during long transit period, is quite different from orbital environment. Vehicle systems, engineering requirements and configurations will be quite different, accordingly.

Note that computational extrapolation of 2pi steradian exposure to deep space radiation on the lunar surface to 4pi steradian in deep space is not a substitute for high fidelity, hard data that can and must be acquired from deep space environment or closest approximation alone.

The methods to be adopted to test the effects and develop countermeasures for radiation are to be evolved from state-of-the-art facilities used now in radiation medicine. Plants and animal specimens are proposed as the first occupants for this lunar orbiting station(Gateway).

Keeping specimen alive and active without crew onboard will require state-of-the-art telepresence and telerobotic systems that are continually monitored and controlled from Earth. Periodic, short crew visits would enable collection of irradiated specimen, rack changeouts and experiments and develop and test and evolve countermeasure strategies.

Ethical rules exist and are strictly adhered to in laboratories around the world and must be followed in the treatment and upkeep of test subject animals.

8. Lunar Orbiting Station(Gateway)Location–Nearside Earth-Moon LPoint EML-1

The Earth-facing Earth-Moon Lagrangian point L1 may offer the better spot for this deep space radiation exposure simulation than any lunar orbital location for the Lunar Orbiting Station(Gateway). It could also serve as a high-bandwith, line-of-sight laser communications node between the Moon and the Earth with 100% link connectivity, obviating the need for satellite constellations. EML-1 better simulates environment for interplanetary vehicle evolution.

If an orbital location is chosen for the Lunar Orbiting Station(Gateway), both low lunar equatorial and polar orbits are better options than the proposed Near Rectilinear Halo Orbit(NRHO). Any orbit and site is achievable from EML-1 and it could be a waystation node and potentially evolve into and Mars Expedition Vehicle departure site.

9. Kilopower Nuclear Fission Reactor Testbed for Power and Propulsion Element

For the proposed Power and Propulsion Element(PPE) onboard the lunar orbiting station(Gateway), the recently NASA certified Kilopower Nuclear Fission reactor could be an ideal testbed. Kilopower could be provide auxiliary power and eventually make way for bimodal nuclear thermal rocket and VASIMR technologies for faster, more compact and efficient crewed interplanetary missions.

10. Low Lunar Orbit for Lunar Orbiting Station(Gateway) Advantages

Low lunar orbital operations for the lunar orbiting station(Gateway) provides some very useful exploration capabilities. Crew can conduct global exploration and site selection for various activities, compare and contrast terrain features, ISRU resources and usefulness, virtually and with telepresence and telerobotic agents, before setting payloads and equipment down on the surface. Orbit-to surface-teleoperations can be a useful asset for lunar or planetary exploration and infrastructure development alike. The study of how crew physiology and performance are impacted by prolonged weightlessness followed by surface activities is also seen as a critical issue that needs hard data and evaluation before countermeasures can be developed and certified. Crew and co-robotic agents working together on the lunar surface can speed up exploration and buildup missions.

11. Global Lunar Prospecting and Sample Return to Lunar Orbiting Station(Gateway)

Using existing technologies, prospecting and sampling for lunar materials is possible. Current planetary rover technologies may be quickly adapted for lunar surface exploration, to propel small lunar samples from various regions to the Lunar Orbiting Station(Gateway) where it may be captured, tests conducted, and even sent back to Earth as mission requirements dictate.

12. Lunar Lava Tube Exploration - Top Scientific Priority

The exploration of lunar lava tubes should be high on the priority list for the entire space science community. Currently we know nothing about the interior of lunar or planetary lava tubes, except that they exist and that there are breaches through which we might be able to access them. The potential of such geologic features to provide natural shelter from the harsh and extreme extraterrestrial environment and to verify potential resources they may hold, is vital to gain a foothold for humanity on the Moon and planets, to become a truly spacefaring species.

13. ISRU for Consumables and Agriculture

Use of natural lunar materials to replenish consumables including breathable atmosphere, potable water, distillation of carbonaceous volatiles, and production of fresh food can impact long duration interplanetary missions, and eventually, the establishment of permanent extraterrestrial settlements.

14. Tourism – Key to Truly Self-Sustainable Human Space Activity in the Immediate Term

And finally, to make human space activity sustainable, space tourism may hold the key in the immediate term. NASA was involved in the first civilian space tourist mission. NASA charter could be expanded to accelerate this vital industry in the 21st century. Using existing assets and infrastructure, including governmental, international, commercial and private enterprise, it is possible to inject revenue generated by space tourism to accelerate human space activity. This activity can begin at ISS with NASA and State Department coordinating with FAA and the Commerce Department, and extend to short tourist visits to the Lunar Orbiting Station Gateway. Immediate benefits include the arrival of rapid "rocketset" travel for the global public using fully reusable vehicles that can provide access to any place on Earth in under 30 minutes.

Conclusion

"Lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations;". – White House Space Policy Directive #1

The US administration has laid out, in the clearest terms yet in many years, what the nation expects NASA to do in the immediate term: Return people to the Moon asap(2020s timeframe) with the goal of building the technological and operational infrastructure to conduct a safe human Mars expedition within the next two decades(2030s).

A fresh new space policy outlook drives an invigorated agency impetus to incorporate homegrown private space companies, that are chomping at the bit with creativity and new visions for utilizing human spaceflight for commerce and profit, and NASA is already showing signs of nurturing many more commercial entities into the core of this vital national endeavor, so the United States can continue to be preeminent in spaceflight, particularly in human space activity.

NASA holds global mystique. NASA has agreements with more than 130 nations to conduct joint missions and space experiments, much more than any other nation has in any complex international endeavor to date. Several robotic spacecraft, many carrying components and equipment developed by international partners are expanding the frontiers of knowledge, from detecting water on our Moon and monitoring Climate Change on Earth, attempting to measure the pulse of Mars, to studying our sun at close range. Some spacecraft are even racing beyond the domain of our solar system. Other missions are currently peering out to gauge the depths of our vast universe, unravelling the mysteries of our Cosmos and our origins and future prospects for our home planet and our species while searching for others.

This alone should prove US preeminence in space activity, not to mention the ISS is the only permanently occupied human crewed orbiting facility that is approaching an unparalleled two decades of continuous operations. Needless to say, NASA folks have their hands full, and is welcoming new partners to begin human missions beyond low Earth orbit.

Commerce is the lifeblood of modern civilization. Commerce is a pillar of national security. Open-ended, taxpayer funded space exploration, by itself, is not sustainable for future long duration missions. Hence the role of commerce and international partners in human space activity. An effort to expand the International Space Station model to include more partners on a global scale is also proceeding in parallel. Citizen supported non-profit organizations play an important role in inspiring the public and providing feedback to NASA and other government space agencies.

The National Space Society, The Planetary Society, The British Interplanetary Society as well as the newly formed international MoonBase Alliance and the Moon Village Association are examples of such organizations that play a vital role in this regard.

The importance of training a new generation of explorers and space professionals across the globe is key to evolving vibrant and progressive space activity initiatives. The educational programs offered by the International Space University by honing promising young and aspiring global leaders as well as providing a unique platform for initiating and catalysing international space activity efforts is unique in character in this regard.

The goal to develop and field the next generation of human occupied space station, one that can safely keep her crew and reliably operate beyond the protective cocoon of the Earth's magnetic field is logically the next step along the critical path for evolving a Mars expedition vehicle, one that has to weather the interplanetary environment, before crew can be safely delivered to the surface of Mars.

While large, heavy lift launch vehicles and planetary landers are being developed, integrated and tested, are there ways to speed up human spaceflight activity? What projects can we do with existing human spaceflight assets that are aligned with administration space policy directives?

The ADAM Project attempts to explore options available in the immediate term, to satisfy the national space policy goals set forth by the current administration, while encouraging new visions for human space activity, utilizing existing space technology to accelerate real space commerce for the immediate benefit of all society.

This paper lists synopses of various concept architectures presented by graduate students in the ASTE527 Space Concepts Studio on December 11th, 2018, the first anniversary of the signing for the Space Policy Directive #1 on December 11, 2017 by the president of the United States of America.

The USC 2018 ADAM Project continues in a long line of past lunar projects that make the case for speedy lunar return. Earlier projects may be accessed at : https://sites.google.com/a/usc.edu/aste527/home

Acknowledgements

Figure 12. Apollo 11 astronaut Buzz Aldrin was guest of honor at the 2018 ADAM Project final presentations

The USC ADAM Project was done in the ASTE527 Graduate Space Concepts Studio in the Fall of 2018. Dr.Buzz Aldrin was guest of honor at finals. We owe thanks for all the visiting lecturers, both from NASA and the industry as well as USC faculty, and industry professionals who engaged the studio. Special thanks to Engineering school dean Yannis Yortos and Astronautical Engineering Chair Michael Gruntman for unwavering support of the studio and to the Astronautical departmental staff for hospitality. Finally, thanks to the dedicated USC Distance Education Network staff that supports our remote students and were very effective in beaming in several lecturers and reviewers from NASA and industry across CONUS without whom we would lack the cutting edge that we so cherish in our graduate studio activities.

"This will not be Lucy and the Football again"
– NASA Administrator Jim Bridenstine

Gateway or Moon ? – When given two good choices, take both !

Truly CAVU – Ceiling and Visibility Unrestricted

General References

Aldrin, B., Byrnes, D., Jones, R., & Davis, H. (2001). Evolutionary space transportation plan for Mars cycling concepts. AIAA Paper, 4677, 2001.

Alexander, R., Chavers, G., & Percy, T. (2018). Robotic Lunar Lander Concept [STUB].

Angelis, D. G., Wilson, J. W., Clowdsley, M. S., Nealy, J. E., Humes, D. H., & Clem, J. M. (2002). Lunar lava tube radiation safety analysis. Journal of radiation research, 43(Suppl), S41-S45.

Arnold,J.R.(1979). Ice in the lunar polar regions. Jour. of Geophysical Research: Solid Earth, 84(B10), 5659-5668.

Augustine, N., Austin, C. D. W., Bejmuk, M. B., Chyba, C., Crawley, E., Greason, M. J.,& Chairman, N. A. (2009). Review of US Human Space Flight Plans Committee. Seeking a Human Spaceflight Program Worthy of a Great Nation," NASA, Washington, DC, Oct.

Autry,G.(2018). Commercial Orbital Transportation Services:CaseStudyNationalIndustrialPolicy.New Space.

Bienhoff, D. (2007, February). The Potential Impact of a LEO Propellant Depot On the NASA ESAS Architecture. In Space Technology & Applications International Forum (STAIR-2007), Albuquerque, NM (pp. 11-15).

Behrens, J. W., Chandler, F. O., & Cronick, J. J. (2009). U.S. Patent No. 7,575,200. Washington, DC: U.S. Patent and Trademark Office.

Blair, D. M., Chappaz, L., Sood, R., Milbury, C., Bobet, A., Melosh, H. J., ... & Freed, A. M. (2017). The structural stability of lunar lava tubes. Icarus, 282, 47-55.

Burke,J.D.(1985).Merits of a lunar polar base location. Lunar Bases and Space Activities of the 21st century(p. 77).

Bussey, D. B. J., McGovern, J. A., Spudis, P. D., Neish, C. D., Noda, H., Ishihara, Y., & Sørensen, S. A. (2010). Illumination conditions of the south pole of the Moon derived using Kaguya topography. Icarus, 208(2), 558-564.

Chandler, F., Bienhoff, D., Cronick, J., & Grayson, G. (2007). Propellant Depots for Earth Orbit and Lunar Exploration. In AIAA SPACE 2007 Conference & Exposition (p. 6081).

Chancellor, J., Scott, G., & Sutton, J. (2014). Space radiation: the number one risk to astronaut health beyond low earth orbit. Life, 4(3), 491-510.

Chappaz, L., Sood, R., Melosh, H. J., Howell, K. C., Blair, D. M., Milbury, C., & Zuber, M. T. (2017). Evidence of large empty lava tubes on the Moon using GRAIL gravity. Geophysical Research Letters, 44(1), 105-112.

Colaprete, A., Schultz, P., Heldmann, J., Wooden, D., Shirley, M., Ennico, K., ... & Goldstein, D. (2010). Detection of water in the LCROSS ejecta plume. science, 330(6003), 463-468.

Connolly, J. F., Drake, B., Joosten, B. K., Williams, N., Polsgove, T., Merrill, R., ... & Percy, T. (2018). The Moon as a Stepping Stone to Human Mars Missions.

Cooper, B. L., Sharpe, B., Schrunk, D., & Thangavelu, M. (2005). Telerobotic exploration and development of the Moon. Journal of earth system science, 114(6), 815-822.

Cohen, M. M. (2002, October). Selected precepts in lunar architecture. In 34th COSPAR Scientific Assembly.

Eckart, P. (Ed.). (1999). The lunar base handbook: an introduction to lunar base design, development, and operations. McGraw-Hill.

Crawford, I. A. (2004). The scientific case for renewed human activities on the Moon.Space Policy, 20(2),91-97.

Crawford, I. A., & Joy, K. H. (2014). Lunar exploration: opening a window into the history and evolution of the inner Solar System. Philosophical transactions. Series A, Mathematical, physical, and engg. sciences, 372(2024).

Crawford, I. A. (2015). Lunar resources: A review. Progress in Physical Geography, 39(2), 137-167.

Crusan, J. C., Smith, R. M., Craig, D. A., Caram, J. M., Guidi, J., Gates, M., ... & Herrmann, N. B. (2018, March). Deep space gateway concept: Extending human presence into cislunar space. In 2018 IEEE Aerospace Conference (pp. 1-10). IEEE.

Crusan, J. C., Craig, D. A., & Herrmann, N. B. (2017, March). NASA's deep space habitation strategy. In Aerospace Conference, 2017 IEEE (pp. 1-11). IEEE.

Cucinotta, F. A., Manuel, F. K., Jones, J., Iszard, G., Murrey, J., Djojonegro, B., & Wear, M. (2001). Space radiation and cataracts in astronauts. Radiation research, 156(5), 460-466.

Cucinotta, F. A. (2015). Review of NASA approach to space radiation risk assessments for Mars exploration. Health physics, 108(2), 131-142.

Delp, M. D., Charvat, J. M., Limoli, C. L., Globus, R. K., & Ghosh, P. (2016). Apollo lunar astronauts show higher cardiovascular disease mortality: possible deep space radiation effects on the vascular endothelium. Scientific reports, 6, 29901.

Edmundson, P., & Thangavelu, M. (2012). Evolution of the Space Cruise Ship" Cosmic Mariner". In AIAA SPACE 2012 Conference & Exposition (p. 5330).

Elfes, A., Weisbin, C. R., Hua, H., Smith, J. H., Mrozinski, J., & Shelton, K. (2008, September). The HURON task allocation and scheduling system: Planning human and robot activities for lunar missions. In Automation Congress, 2008. WAC 2008. World (pp. 1-8). IEEE.

Fong, T., & Thorpe, C. (2001). Vehicle teleoperation interfaces. Autonomous robots, 11(1), 9-18.

Fong, T., Abercromby, A., Bualat, M. G., Deans, M. C., Hodges, K. V., Hurtado Jr, J. M., ... & Schreckenghost, D. (2010). Assessment of robotic recon for human exploration of the Moon. Acta Astronautica, 67(9-10), 1176-1188.

French, B. M., Heiken, G., Vaniman, D., & Schmitt, J. (1991). Lunar sourcebook: A user's guide to the Moon.

Gernhardt, M., Abercromby, A., & Braham, S. (2009). Engineering evaluation of Lunar Electric Rover 1B and Portable Utility Pallet during simulated planetary surface exploration. EVA Physiology, Systems, and Performance Project, NASA Johnson Space Center, Houston, TX.

Gernhardt, M. L., Jones, J. A., Scheuring, R. A., Abercromby, A. F., Tuxhorn, J. A., & Norcross, J. R. (2009). Risk of compromised EVA performance and crew health due to inadequate EVA suit systems. Human health and performance risks of space exploration missions: evidence reviewed by the NASA Human Research Program. Washington, DC: Government Printing Office, 333-58.

Gibson, M. A., Mason, L. S., Bowman, C. L., Poston, D. I., McClure, P. R., Creasy, J., & Robinson, C. (2015). Development of NASA's Small Fission Power System for Science and Human Exploration.

Greeley, R. (1971). Lava tubes and channels in the lunar Marius Hills. The Moon, 3(3), 289-314.

Gerstenmaier, W. H., & Ticker, R. L. (2007). International Systems Integration on the International Space Station.

Griffin, B. (2012, July). Benefits of a single-person spacecraft for weightless operations. In 42nd International Conference on Environmental Systems (p. 3630).

Haruyama, J., Hioki, K., Shirao, M., Morota, T., Hiesinger, H., van der Bogert, C. H., ... & Matsunaga, T. (2009). Possible lunar lava tube skylight observed by SELENE cameras. Geophysical Research Letters, 36(21).

Häuplik-Meusburger, S. (2011). Architecture for astronauts: an activity-based approach. Springer Science & Business Media.

Horz, F. (1985). Lava tubes-Potential shelters for habitats. In Lunar bases and space activities of the 21st century

Haruyama, Junichi, et al. "Possible lunar lava tube skylight observed by SELENE cameras." Geophysical Research Letters 36.21 (2009). DOI: 10.1029/2009GL040635. Link: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2009GL040635.

Haruyama, J., Morota, T., Kobayashi, S., Sawai, S., Lucey, P. G., Shirao, M., & Nishino, M. N. (2012). Lunar holes and lava tubes as resources for lunar science and exploration. In Moon (pp. 139-163). Springer, Berlin, Heidelberg.

Howe, A. S., & Sherwood, B. (Eds.). (2009). Out of this world: The new field of space architecture. American Institute of Aeronautics and Astronautics.

Huber, S. A., et al. "Astrobotic Technology: Planetary pits and caves for science and exploration." Annual Meeting of the Lunar Exploration Analysis Group. Vol. 1820. 2014. Link: https://www.hou.usra.edu/meetings/leag2014/pdf/3065.pdf.

Jolliff, B. L., Wieczorek, M. A., Shearer, C. K., & Neal, C. R. (Eds.). (2018). New views of the Moon (Vol. 60). Walter de Gruyter GmbH & Co KG.

Kabe, A. (1998, April). Design and verification of launch and space vehicle structures. In 39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit (p. 1718).

Kabe, A. M., & Kendall, R. L. (2010). Launch Vehicle Operational Environments. Ency. of Aerospace Engineering.

Kaku, Tetsuya, et al. "Detection of intact lava tubes at Marius Hills on the Moon by SELENE (Kaguya) Lunar Radar Sounder." Geophysical Research Letters 44.20 (2017): 10-155. DOI: 10.1002/2017GL074998. Link: http://asrl.ua.edu/uploads/1/0/6/7/106772759/kaku_et_al-2017-geophysical_research_letters.pdf.

Kerber, L., et al. "Moon diver: A discovery mission concept for understanding the history of the mare basalts through the exploration of a lunar mare pit." New Views of the Moon 2-Asia. Vol. 2070. 2018. Link: https://www.hou.usra.edu/meetings/lpsc2018/pdf/1956.pdf.

Khoshnevis, B., Carlson, A., Leach, N., & Thangavelu, M. (2012). Contour crafting simulation plan for lunar settlement infrastructure buildup. In Earth and Space 2012: Engineering, Science, Construction, and Operations in Challenging Environments (pp. 1458-1467).

Khoshnevis, B., Thangavelu, M., Yuan, X., & Zhang, J. (2013). Advances in contour crafting technology for extraterrestrial settlement infrastructure buildup. In AIAA SPACE 2013 Conference and Exposition (p. 5438).

Kring, D. A., & Durda, D. D. (2012). A global lunar landing site study to provide the scientific context for exploration of the Moon. LPI Contribution, (1694).

Lali, M., & Thangavelu, M. (2016). MOBIUS: An Evolutionary Strategy for Lunar Tourism. In AIAA SPACE 2016

Lii, N. Y., Leidner, D., Schiele, A., Birkenkampf, P., Pleintinger, B., & Bayer, R.(2015, March). Command robots from orbit with supervised autonomy: An introduction to the METERON supervision experiment. In Proceedings of the Tenth Annual ACM/IEEE International Conference on Human-Robot Interaction Extended Abstracts

Laurini, K. C., & Gerstenmaier, W. H. (2014). The Global Exploration Roadmap and its significance for NASA. Space Policy, 30(3), 149-155.

Mendell, W. W. (1985). Lunar bases and space activities of the 21st century.

Mankins, J., & Reibaldi, G. (2018, July). The Moon Village Association: An informal, global forum for cooperation and coordination in lunar exploration. In 42nd COSPAR Scientific Assembly (Vol. 42).

Mason, L., Palac, D., & Gibson, M. (2017). Kilopower: Small and Affordable Fission Power Systems for Space.

Miller, C., Wilhite, A., Cheuvront, D., Kelso, R., McCurdy, H., & Zapata, E. (2015). Economic assessment and systems analysis of an evolvable lunar architecture that leverages commercial space capabilities and public-private-partnerships. NexGen Space LLC under grant from NASA.

NASA(2018) International Space Station Transition Report, pursuant to Section 303(c)(2) of the NASA Transition Authorization Act of 2017 (P.L. 115-10)

NASA(2018) National Space Exploration Campaign Report, Pursuant to Section 432(b) of the NASA Transition Authorization Act of 2017 (P.L. 115-10), September 2018

National Research Council. (2010). Guide for the care and use of laboratory animals. National Academies Press.

National Research Council & Space Studies Board.,(2012). Vision and voyages for planetary science in the decade 2013-2022. National Academies Press.

National Research Council & Space Studies Board,(2012). Technical evaluation of the NASA model for cancer risk to astronauts due to space radiation. National Academies Press.

Neal, C. R.(2009).The Moon 35 years after Apollo: What's left to learn?.Chemie der Erde-Geochemistry,69(1),3-43.

Nesnas, Issa AD, et al. "Axel and DuAxel rovers for the sustainable exploration of extreme terrains." Journal of Field Robotics 29.4 (2012): 663-685. DOI: 10.1002/rob.21407.

Nixon, D. (2016). International Space Station: Architecture Beyond Earth. Circa Press.

Pieters, C. M., Boardman, J., Buratti, B., Chatterjee, A., Clark, R., Glavich, T., ... & McCord, T. (2009). The Moon Mineralogy Mapper (M^3) on Chandrayaan-1. Current Science, 500-505.

Raftery, M., & Hoffman, J. (2013). International space station as a base camp for exploration beyond low Earth orbit. Acta Astronautica, 85, 25-32.

Ride, S. K. (1987). Leadership and America's future in space.

Roukos, D., & Thangavelu, M. (2010, September). Construction of an International Space Transit Vehicle Using the Space Station. In AIAA SPACE 2010 Conference & Exposition (p. 8876).

Sadler, P., Giacomelli, G., Furfaro, R., Patterson, R., & Kacira, M. (2009). Prototype BLSS lunar greenhouse (No. 2009-01-2484). SAE Technical Paper.

Schrunk, D., Sharpe, B., Cooper, B. L., & Thangavelu, M. (2007). The Moon: Resources, future development and settlement. Springer Science & Business Media.

Seedhouse,E. (2009). Lunar outpost (pp. 121-149). Praxis.

Silverman, J., Suckow, M. A., & Murthy, S. (Eds.). (2014). The IACUC handbook. CRC Press.

Sood, R., Chappaz, L., Melosh, H. J., Howell, K. C., Milbury, C., Blair, D. M., & Zuber, M. T. (2017). Detection and characterization of buried lunar craters with GRAIL data. Icarus, 289, 157-172.

Spudis, P. D. (1996). The once and future moon. The once and future moon/Paul D. Spudis. Washington: Smithsonian Institution Press, c1996.(Reprint of hardcover original..) QB 581 S686 1996.

Stafford, T. P. (1991). America at the threshold: report. Supt. of Docs., USGPO.

Thangavelu, M., & Dorrington, G. E. (1988). MALEO-Strategy for lunar base build-up. In IAF, International Astronautical Congress, 39th, Bangalore, India (p. 1988).

Thangavelu, M., & Mekonnen, E. (2009). Preliminary Infrastructure Development for Altair Sortie Operations. AIAA SPACE 2009 Conference & Exposition (p. 6422).

Thangavelu, M. (2010). Living on the Moon. Encyclopedia of Aerospace Engineering.

Thangavelu, M., Khoshnevis, B., Carlson, A., & Leach, N. (2012). Architectural concepts employing co-robot strategy and contour crafting technologies for lunar settlement infrastructure development. In AIAA SPACE 2012 Conference & Exposition (p. 5173).

Thangavelu,M.(2014).Planet Moon: Future of Astronaut Activity & Settlement.Architectural Design,84(6),20-29.

Thangavelu,M.&Vasmate,V.(2016)LUNARSENTINEL: Planetary Defense from the Moon. AIAA SPACE 2016

Thangavelu, M., & Burke, J. D.(2017) ADVANCES IN MALEO. IAC Guadalajara, Mexico.

Thangavelu, M. ed.Aghdasi, F., Caillouet, T., Chao, A., Ives, B., Lali, M., Perakalpudi, N. V., ... & Vasmate, V.(2017) LunaRevolution-Role of the Moon in the Future of Human Space Activity. IAC Guadalajara, Mexico

Turner, R., & Kunkel, R. (2017, July). Radiation Environment inside a Lunar Lava Tube. 47th International Conference on Environmental Systems.

Urey, H. C. (1967). Water on the Moon. Nature, 216(5120), 1094-1095.

White House(2017) Presidential Memorandum on Reinvigorating America’s Human Space Exploration Program

White House(2018) Streamlining Regulations on Commercial Use of Space

White House(2018)Space Policy Directive-3, National Space Traffic Management Policy

Weisbin, C. R., & Lavery, D. (1994). Nasa rover and telerobotics technology program. IEEE Robotics & Automation Magazine, 1(4), 14-21.

Weisbin, C., Mrozinski, J., Hua, H., Shelton, K., Smith, J. H., Elfes, A., ... & Silberg, R. (2008, August). Human-robot lunar exploration: Pressurized vs. unpressurized rovers. In Systems Engineering, 2008. ICSENG'08. 19th International Conference on (pp. 8-12). IEEE.

Whittaker, W. I. L. L. I. A. M. (2012). Technologies enabling exploration of skylights, lava tubes and caves. NASA, US, Report, no. NNX11AR42G.

Yazdi, K., & Messerschmid, E. (2008). A lunar exploration architecture using lunar libration point one. Aerospace Science and Technology, 12(3), 231-240.

Zacny, Kris, et al. "Axel rover NanoDrill and PowderDrill: Acquisition of cores, regolith and powder from steep walls." 2013 IEEE Aerospace Conference. IEEE, 2013. DOI: 10.1109/AERO.2013.6497188