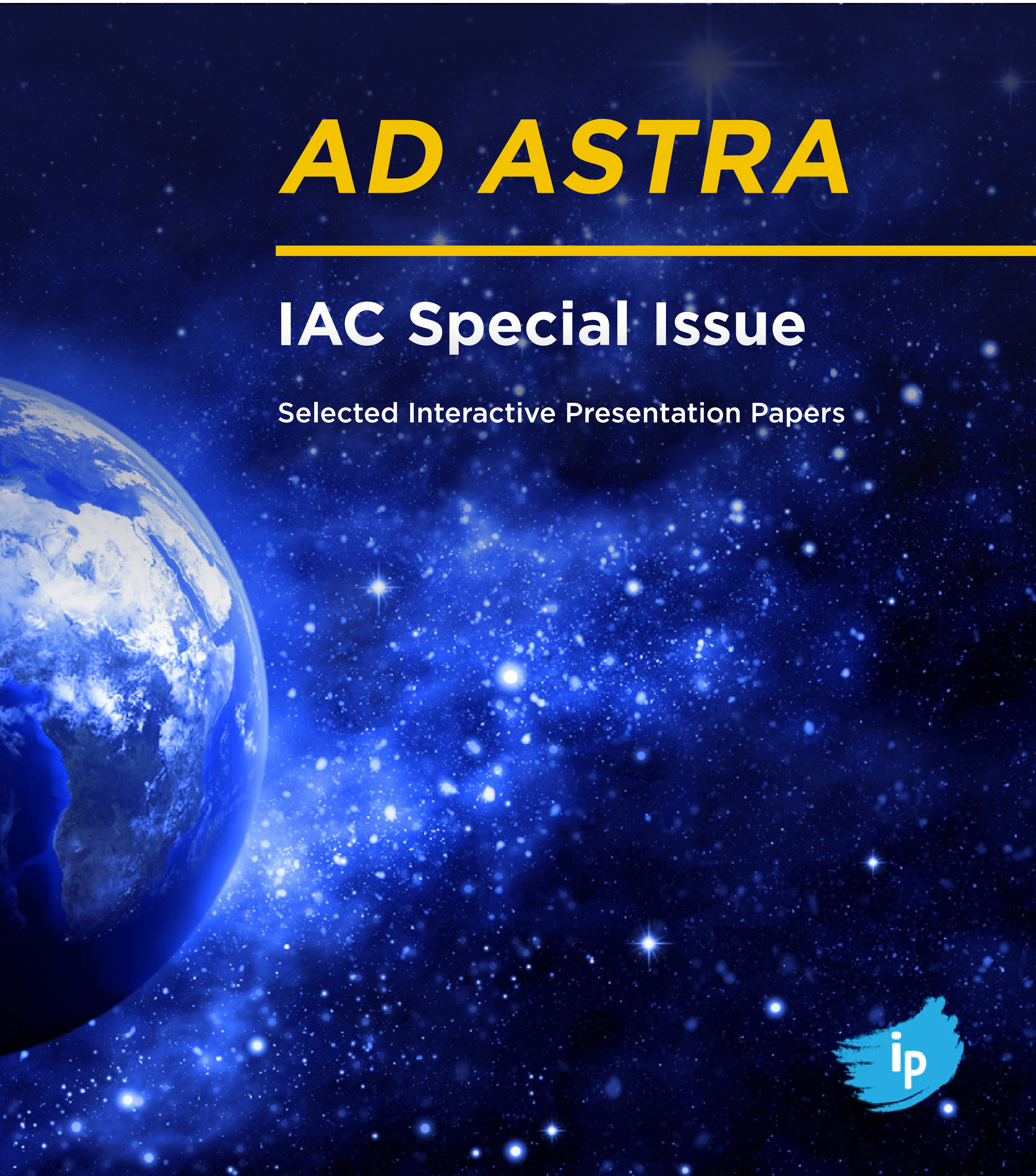
AD ASTRA

IAC Special Issue

Selected Interactive Presentation Papers



Created by the International Astronautical Federation (IAF) and printed by the Chinese Society of Astronautics.

First Issue - 70th International Astronautical Congress - 21-25 October 2019, Washington D.C. - Unites States

Welcome Message

It is with much joy and anticipation that we celebrate the launch of "*Ad Astra*" with this inaugural IAC Special Issue. On behalf of the International Programme Committee, we would like to extend a very warm welcome to the readership of *Ad Astra*. We take this opportunity to thank our authors, co-authors and reviewers, our IAF Alliance Partner - the Chinese Society of Astronautics, and all of whom have volunteered to contribute to the success of *Ad Astra*. An enormous amount of work has been done for the development of this Special Issue, and we believe you will see this effort reflected in this edition and the impact it will have on the space field. It has been an interesting journey in many aspects.

Ad Astra contains a selection of 13 papers that will be presented during the IAC 2019 Interactive Presentations Session on Thursday 24 October. The reviewers have a fiduciary responsibility to the readership to ensure that only high-quality papers appear in the Special Issue. Accordingly, we have "raised the bar" for acceptance. For a paper to appear in *Ad Astra*, it must not only be methodologically immaculate but also have substantial conceptual novelty and a potentially large impact on the space field.

We want to encourage more contributions from the international space community to ensure a continued success of the IAC Special Issue. Authors, but also guest editors are always welcome. We also welcome comments and suggestions that could improve the quality of the Special Issue. We invite everyone to participate in the creative process that we are undertaking together.

We hope you will find *Ad Astra* informative.

Enjoy your reading! Thank you.

Jean-Yves Le Gall
President,
International Astronautical Federation (IAF),
France

Pascale Ehrenfreund
Incoming President and Vice-Precident Communications, Publications And Global Conferences,
International Astronautical Federation (IAF),
France

Welcome Message

Dear Readers,

I take great pleasure in welcoming you to *"Ad Astra"*, our new IAC Special Issue which contains a selection of papers that will be presented at the IAC 2019 Interactive Presentations' Session on Thursday 24 October.

I would like to take this opportunity to acknowledge all the authors who contributed to this inaugural IAC Special Issue. I am grateful to all our reviewers for their time and effort in reviewing the papers and providing us and the authors valuable review comments. I am thankful to our IAF Alliance Partner - the International Society of Astronautics for their strong support in producing and launching this Special Issue. Our vision is to create a high-quality Special Issue that will be relevant, challenging, thought-provoking, and inclusive of a diverse range of voices and perspectives, including academic researchers and scholars, policy-makers, and students. Together, the 13 papers in this special issue reflect the rich variety of topics addressed by the space field and depth of theoretical, methodological, and practical approaches and challenges underpinning this year's Congress Theme *"Space: The Power of the Past, the Promise of the Future".*

Based on the three review criteria on technical contributions, novelty, and completeness, 13 papers were provisionally accepted and requested for quality improvements according to the reviewers' comments and suggestions. This message not only delineates the paper submission, thorough review, and quality assurance of the Special Session papers, but also significantly appreciates the authors' patience for paper revisions according to the comments. I am also keen to hear your constructive ideas and suggestions for helping the growth of this new born but promising IAC Special Issue.

We are delighted that you are joining us as readers and hope you will also join us next year as contributors. Thank you all.

S. Somanath
Vice-President for Technical Activities,
International Astronautical Federation (IAF),
France

Contents

AD ASTRA – IAC Special Issue – 2019

IAC-19-A3,IP,8,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 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.

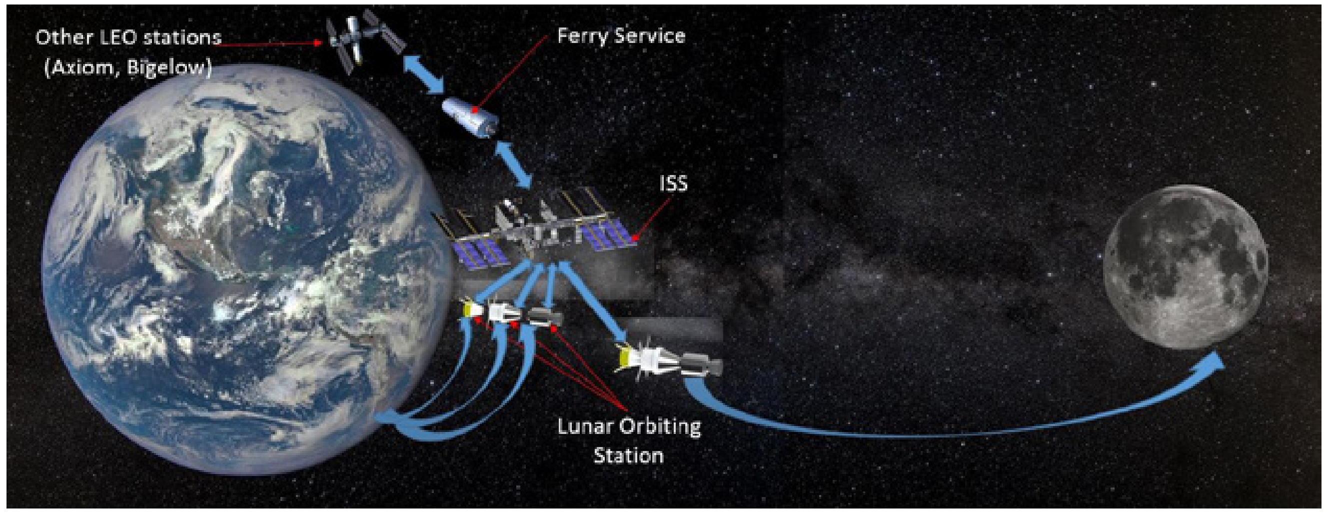


***Figure 1**. The International Space Station (ISS), which was originally conceived to be "an assembly capability from which large space structures and systems are assembled and verified", will provide a valuable platform to build and test the LOS in LEO, even though the facility might not be in the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

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. [see Figure 2]

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

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

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

AD ASTRA – IAC Special Issue – 2019

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]

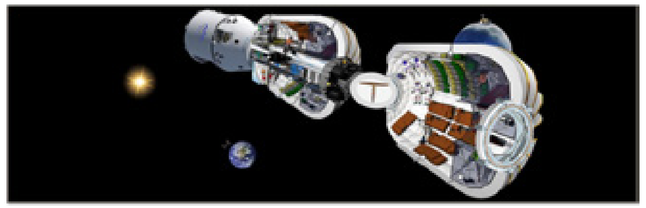


Figure 3. *Deep Space Radiation tests may be conducted at ARTEMIS at the Earth-Moon L1 point*

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. [see Figure 4]

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

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, 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

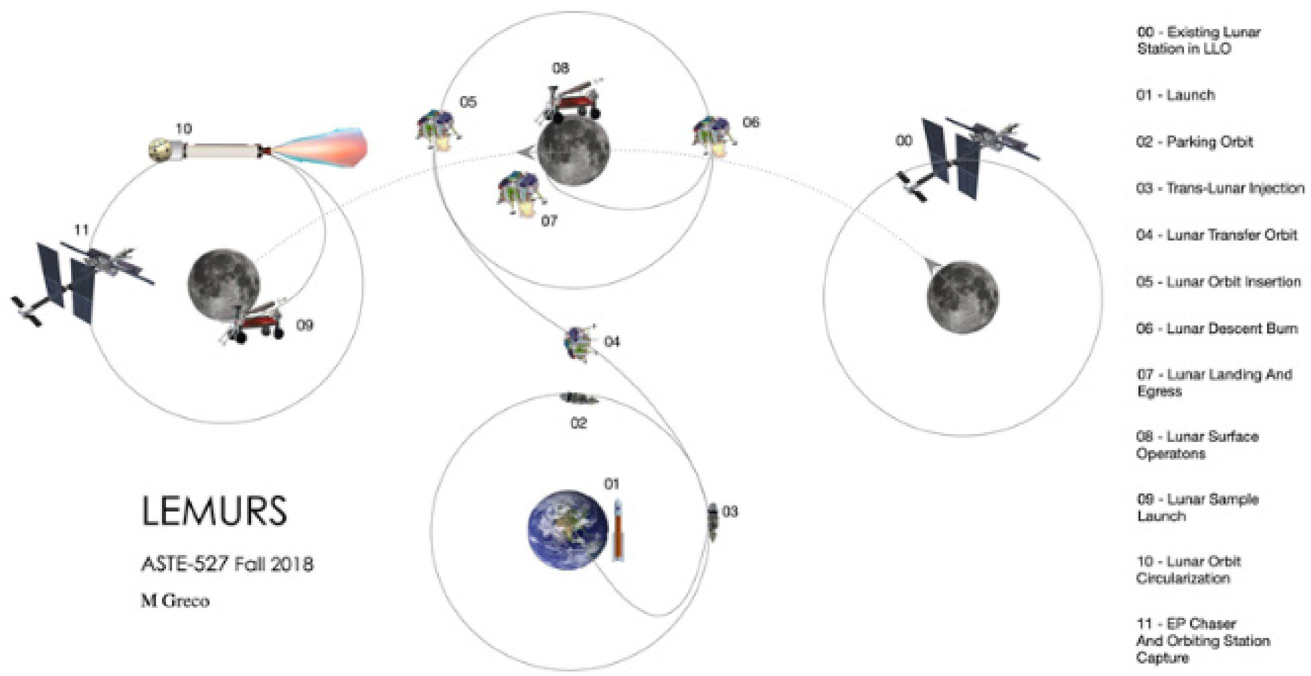


Figure 4. *LEMURS concept proposes electromagnetic propellant-less launch of lunar samples and electric propulsion assisted sample capture and rendezvous system for prospecting from lunar orbiting station(Gateway)*

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.

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]

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

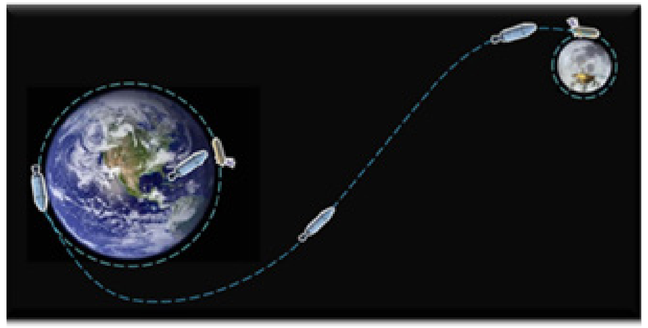


Figure 5. *Strategic Caching can lower costs and extend mission range and also enhance crew safety*

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]

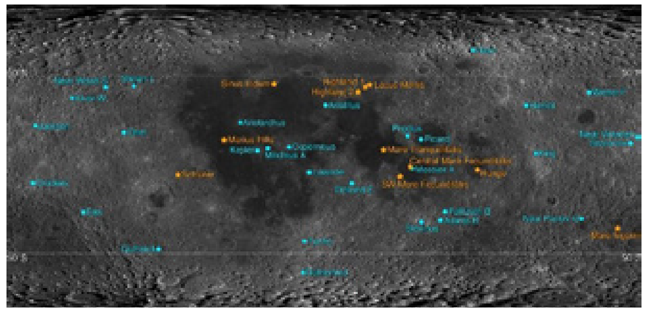


Figure 6. *Recent discovery of roof breaches called "skylights" would allow exploration of lunar lava tubes*

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]

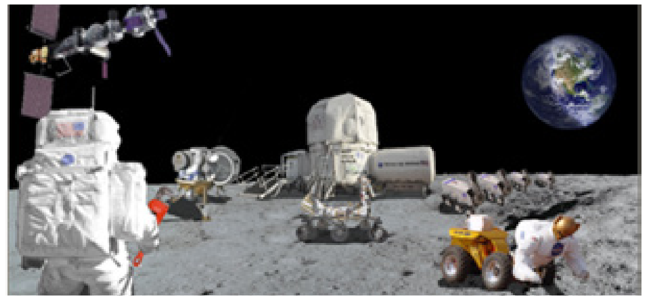


Figure 7. *A lunar orbiting station(Gateway)can support prompt lunar surface operations anomaly resolution across the globe by deploying crew from orbit as and when needed. This is a vital technology for future planetary exploration*

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]

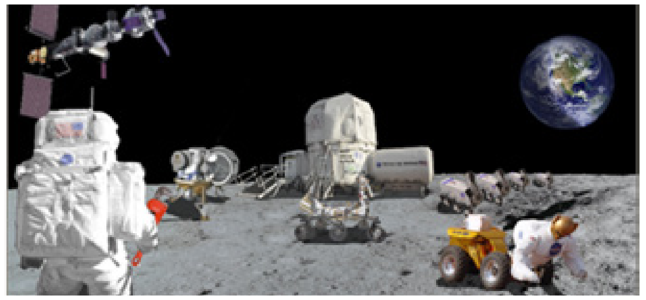


Figure 8. *Using augmented lunar resources and following the lunar day/night cycle to produce fresh food for crew would be a critical step in developing a truly efficient spacefaring capability for humanity.*

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 has 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.

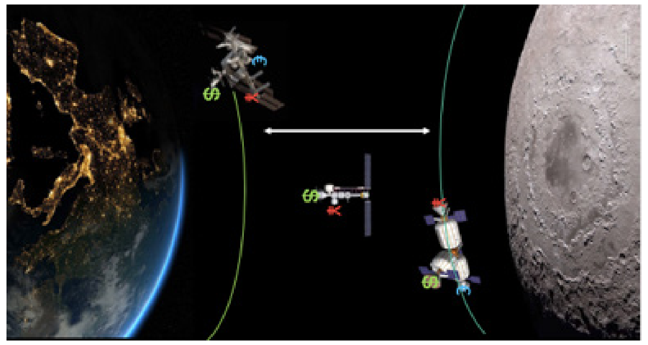


Figure 10. *From Earth orbit to lunar orbit, space tourism is the low-hanging fruit that is ready to jumpstart a truly spacefaring economy*

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

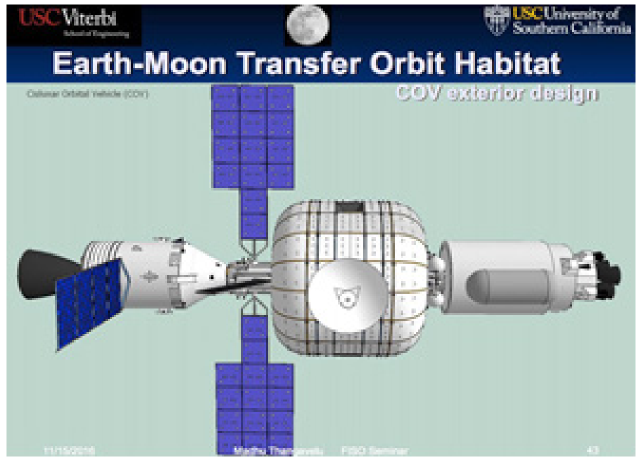


Figure 11. ***T****he MOBIUS architecture proposes mostly existing space systems and employs supersynchronous orbits to bring tourists on close approaches to the Moon.*

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, unraveling 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.

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 for 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: Case Study for National Industrial Policy. 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. In 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).LUNAR SENTINEL: 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

IAC-19,B4,IP,22,x53090

Advances in the UCHSat-1 Nanosatellite: Design and Simulation

Avid Roman-Gonzalez*, Antony E. Quiroz-Olivares, Natalia I. Vargas-Cuentas

Image Processing Research Laboratory (INTI-Lab), Universidad de Ciencias y Humanidades, Av. Universitaria 5175, Los Olivos, Lima, Peru, avid.roman-gonzalez@ieee.org
* Corresponding Author

Abstract

In 2015, at the Image Processing Research Laboratory (INTI-Lab) of the Universidad de Ciencias y Humanidades, one proposed the INCA programme (Research Programme on Aerospace Sciences). As a part of this programme, the design of a nanosatellite was included. Although the progress was plodding, after three years one wants to show these advances. One of the main limitations to have access to space, especially for developing countries, is the high cost of missions. In this sense, in the present work, we propose the use of commercial electric, electronic and electromechanical (EEE) devices, these being more economical than those for military use. UCHSat-1 nanosatellite advances are mainly at the simulation level. It is a CubeSat of 3 units that can be simulated with the help of the beeApp tool of Open Cosmos. Likewise, the nanosatellite modules are being implemented as a function of Arduino Nano. The obtained results show, at least in the first instance, the feasibility of the use of Arduino Nano for the implementation of the different nanosatellite modules.

Keywords: Arduino Nano, Open Cosmos, Simulation, 3U CubeSat, INTI-Lab

1. Introduction

In recent years, the design, implementation, and deployment of nanosatellites have increased exponentially, especially in developing countries. In many cases, these nanosatellites use commercial components known as COTS (Commercial Off-The-Shelf), which makes it possible to reduce the costs of the mission.

Peru is no stranger to this growth since 3 Peruvian universities have already put their nanosatellites in orbit [1]. It is the Pontificia Universidad Catolica del Peru with the PUCPsat-1 and the PockePUCP [2, 3, 4], the Universidad Nacional de Ingenieria with the Chaski-I [5, 6, 7, 8, 9], and the Universidad Alas Peruanas with the UAPSat [10, 11, 12].

The Universidad de Ciencias y Humanidades does not want to be left behind, and that is why, in 2015, through the Image Processing Research Laboratory (INTI-Lab) propose the Research Program on Aerospace Sciences (INCA Program for its acronym in Spanish) [13]. This program includes the design, implementation, and put into orbit a nanosatellite that will be called UCHSat, among other projects.

The use of the COTS electric, electronic, and electromechanical (EEE) components will allow a reduction of the costs of a nanosatellite mission.

In recent years, the term "Space COTS" developed in Germany has been designed to indicate those commercial components that have been qualified for use in space. Although the use of COTS in space missions has already been mentioned since the 2000s, the term Space-COTS was born in recent years. [14, 15, 16].

Due to the technological advancements, nanosatellites missions have been achieved not only for educational purposes but also for more scientific tasks, in the same way.

The continuation of this work is as follow; Section 2 shows the methodology developed for designing and simulating the nanosatellite. In Section 3, authors present the obtained results of the simulation and very first implementation based on Arduino Nano. Finally, Section 4 presents the discussion and conclusions.

2. Design of the UCHSat

The UCHSat will be a CubeSat of 3 units based mainly on Arduino Nano platforms. Figure 1, Figure 2, and Figure 3 show an artistic illustration of what is expected to be achieved.

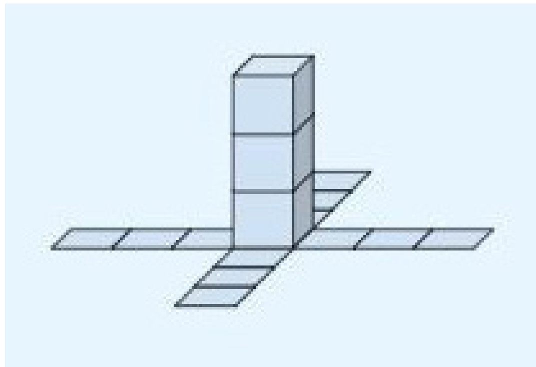


Fig. 1. 3U CubeSat platform chosen for the UCHSat-1

All satellites have the following well known basic modules [13, 17]:

- On-Board Computer (OBC)
- Power Source Module (PSM)
- Communications Module (COM)
- Thermal Control Module (TCM)
- Attitude Control Module (ACM)
- Structure Module (STM)
- Payload Module (PLM)

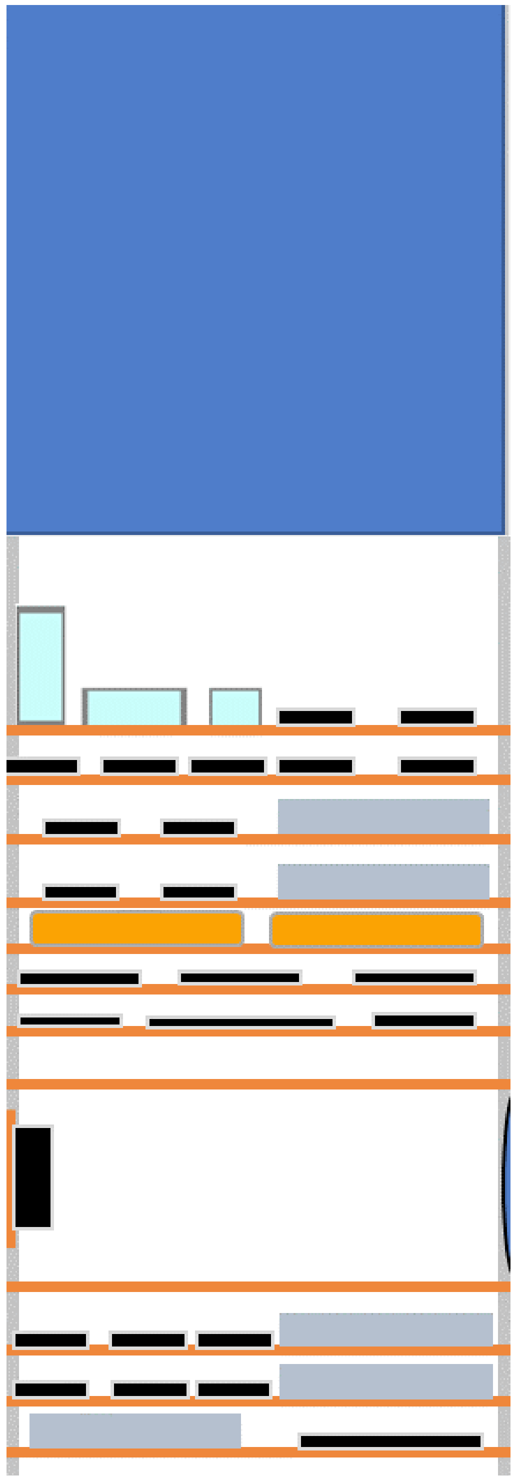


Fig. 2. Distribution of the different modules of the UCHSat-1

All nanosatellite has limitation respecting to power resources, its size, and its weight. In this sense, the idea is to design a very efficient and low power consuming platform. One will include a robust and redundant design for reducing the failure rate in the CubeSat. All the electric, electronic, and electromechanical (EEE) components will have a ceramic or metal package and a wide operating temperature range.

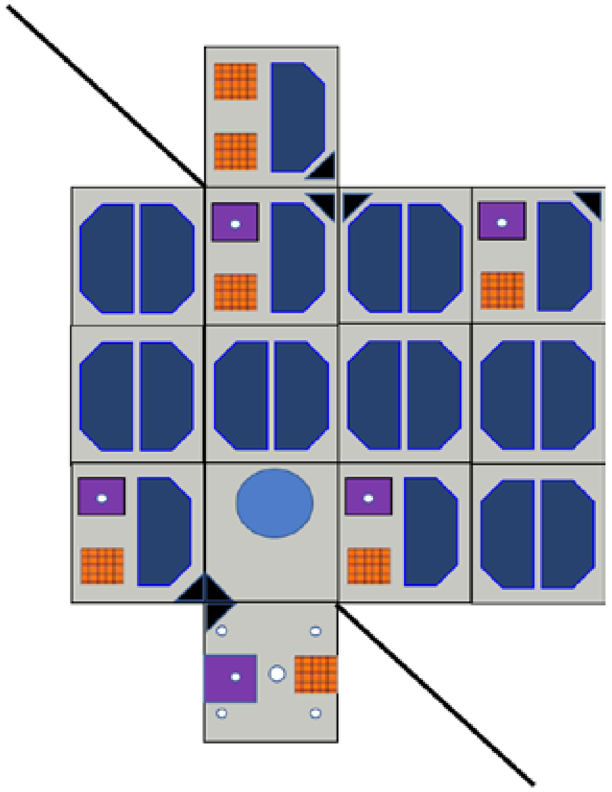


Fig. 3. Exterior surfaces of the nanosatellite UCHSat-1

2.1 On-Board Computer (OBC)

As mentioned above, the UCHSat-1 will be based on Arduino Nano platform; in this sense, the main component of the OBC would be an Arduino Nano. It works with 5 V and has enough interfaces to control all the other satellite modules. The Arduino Nano has the following features:

- Frequency: 16 MHZ
- Flash Memory: 32 KB
- EEPROM: 1 KB
- SRAM memory (internal): 2 KB
- Analog Input Pins: 6 (A0 – A5)
- Digital I/O Pins: 14 (Out of which 6 provide PWM output)
- Communication: IIC, SPI, USART

2.2 Power Source Module (PSM)

The PSM would be implemented with the combination of a set of solar cells, Lithium-Ion batteries, and the electronic control system to regulate and distribute the power to the CubeSat. The reload cycles is essential for a battery long live. The electronic control system will take care of the

best reload cycles and power consumption, continually monitoring the status level of the batteries. For a 3U CubeSat, a nominal power consumption of 6W (+/- 1) can be expected. This power source permits the satellite to be operational during sunlight and eclipse. In the present design, the following components will be used:

- Solar Cells with a 3gr of weight and an efficiency of 27 %.
- Li-Ion batteries with a capacity of 1300 mAh or higher.
- ADP3810 battery charger controller.
- DC-DC converter and adjustable MAX1745 with output voltage from 1.25 V to 18 V.
- DC-DC converter MAX1744 with an output voltage of 5 V or 3.3 V.

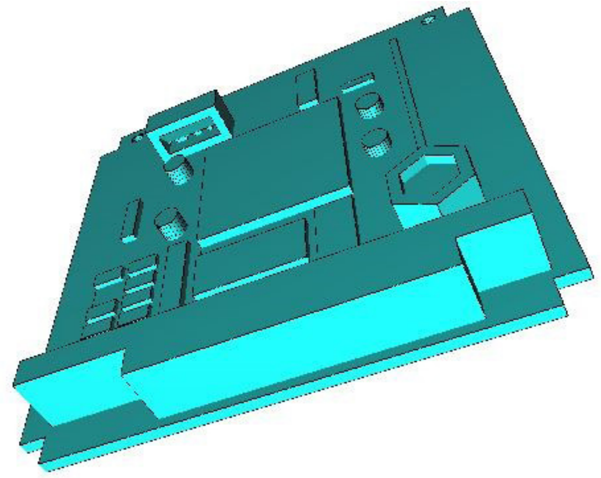


Fig. 4. Example of a module for a 3D Printed version

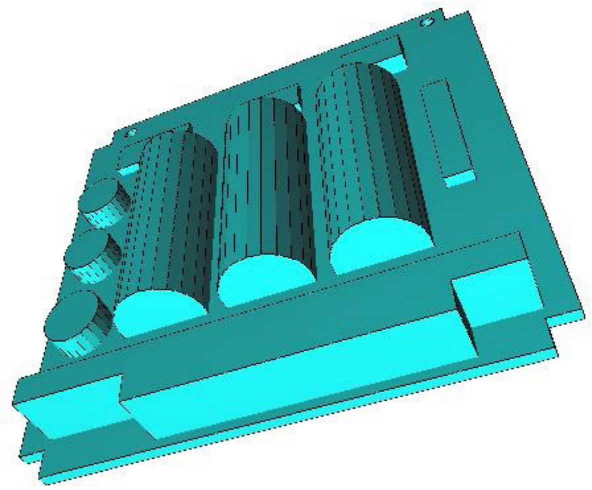


Fig. 5. Example of a power source module for a 3D printed version

2.3 Communications Module (COM)

The communication module would be implemented using a modem that could be i900-000-DIL or similar, which converts the digital data in an analog signal. This analog signal will go to the antenna and transmitted to the ground station. The most used communication standard is AX.25, so, UCHSat-1 will use the same standard for packaging purposes. The working frequency for transmission and reception will be UHF (the exact allocated frequency will be according to the authorization of the Ministry of Communication and Transport of Peru).

2.4 Thermal Control Module (TCM)

The temperature will be monitored by a temperature sensor that could be the LM75 or similar. Heating could also be possible by using a thermostat, for example, the DS1821 or similar. The idea is to regulate the temperature inside of the UCHSat-1 in a typical range between -20°C and +60°C for saving the operational condition of sensible electronic components.

2.5 Attitude Control Module (ACM)

The ACM system will consist of two different subsystems. The first one will be a sensor set of Sun sensors, magnetometers, and gyroscopes to determine the satellite position; the second subsystem will be based on an actuator set of magnetic coils and micro-reaction wheels. The idea is that the UCHSat-1 ACM system could have an accuracy of +/- 5°. The ACM will have its own Arduino Nano (slave) to manage the complex required calculations of the attitude control.

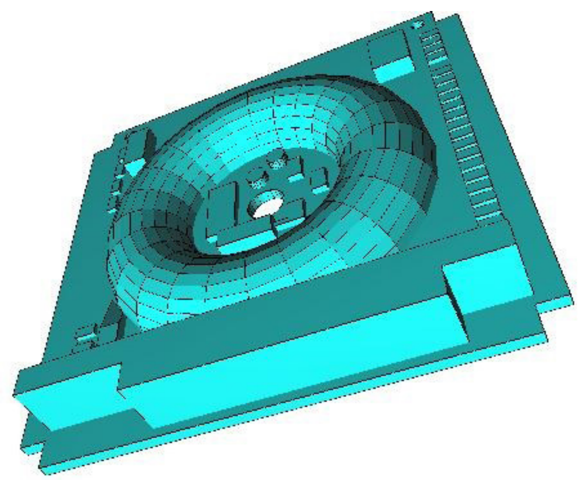


Fig. 6. Example of an attitude control module for a 3D printed version

2.6 Structure Module (STM)

The design of the structure will comply with the requirements of the ISIPOD container. The idea is to use specific types of duralumin like 5052 H32, 6061 T6, and 7075 T6. The solar panels will be fixed over the structure.

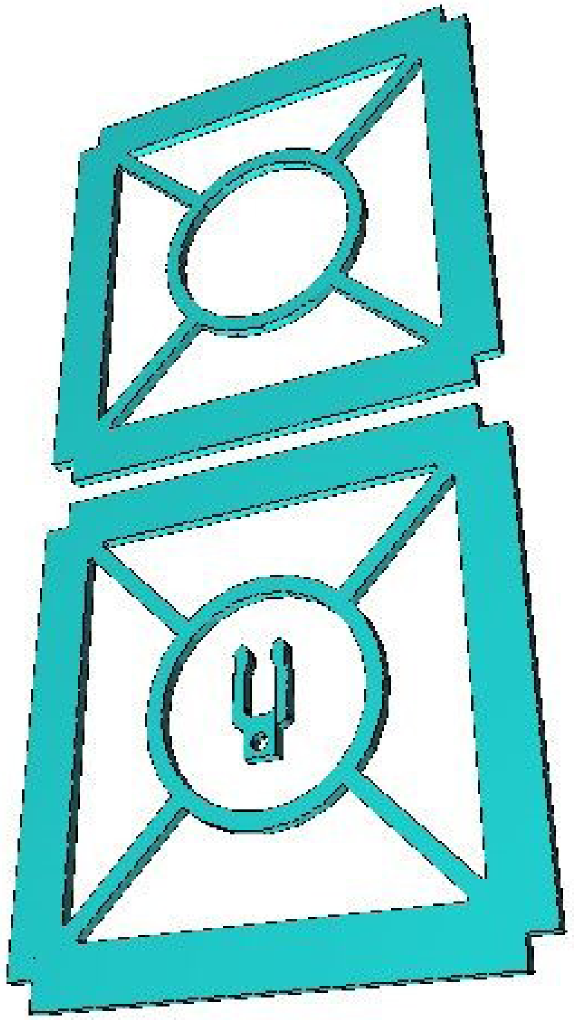


Fig. 7. Example of the structure top and bottom of a CubeSat for a 3D printed version

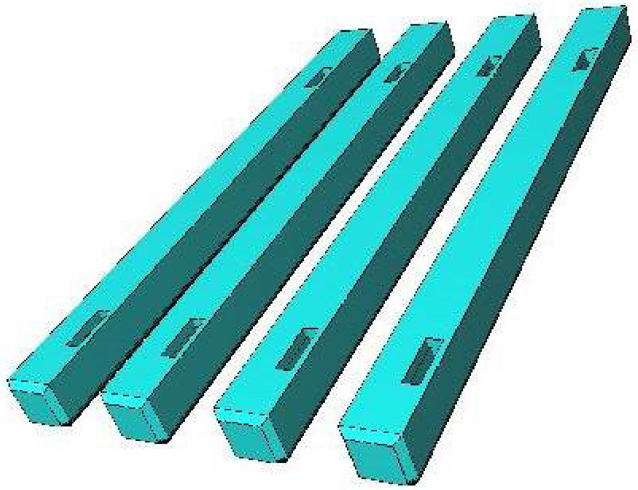


Fig. 8. Example of the structure rails of a CubeSat for a 3D printed version

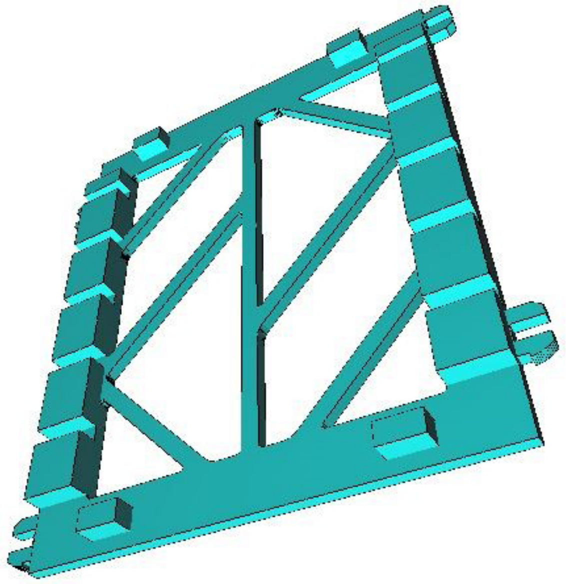


Fig. 9. Example of the structure side of a CubeSat for a 3D printed version

2.7 Payload Module (PLM)
For the UCHSat-1 has been thought of having a camera as a payload. The camera will have the ability to take color or grayscale photos, including the ability to record videos.

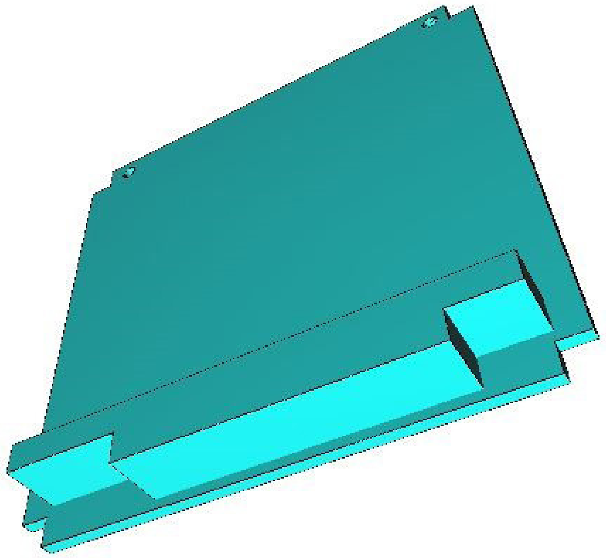


Fig. 10. Example of a board for any nanosatélites module for a 3D printed version

Adding the approximate weights of the different modules, one has the following table with approximately 3 Kg for UCHSat-1:

AD ASTRA – IAC Special Issue – 2019

Table 1. Mass budget

Module	Mass (gr)
OBC	70
PSM	340
COM	200
TCM	160
ACM	230
STM	200
PLM	900
Hardness	450
Margin	150

Margin 150

Respect to the power consumption, one has the following table with approximately 6.4 W for UCHSat-1:

Table 2. Mass budget

Module	Power (W)
OBC	0.3
PSM	0.1
COM	2
TCM	1
ACM	1
PLM	2

3. Simulation Results

Nowadays 3D printing is beneficial in different fields of engineering and other branches such as the design of prostheses, printing of circuit and housings equipment, development of models and maquettes, model preparation for chirurgical operations, among others [18]. In this sense, within the UCHSat-1 project, one also searched for a 3D printed version of a 1U CubeSat model to be the motivation and to mark the way forward. But not only to have a 3D printing model, but one also has the advance of each one of the modules based on Arduino Nano. These advances can be seen in Figure 12.

For the simulation of the UCHSat-1 one will use the Open Cosmos beeApp tool. Open Cosmos (https://www.open-cosmos.com/) is a company founded in 2015 and which is currently under the incubation of the European Space Agency (ESA). Open Cosmos, within its different solutions, offers the beeApp tool that is a specially developed cloud software.

In INTI-Lab, one has access to use the beeApp thanks to the agreement signed between the Universidad de Ciencias y Humanidades and Open Cosmos. The simulation was as follow.

3.1 Payload Parameters
The payload will have two working modes. The first mode is by default with a low power consumption of around 0.1 W since the camera is in standby mode. The second mode is when the camera takes pictures; in this mode, the payload consumes about 2 W. In Figure 13, one can see a screenshot of the parameters of the payload for the simulation. The pictures taken by the camera will produce a data rate of 1.4 Mbps.

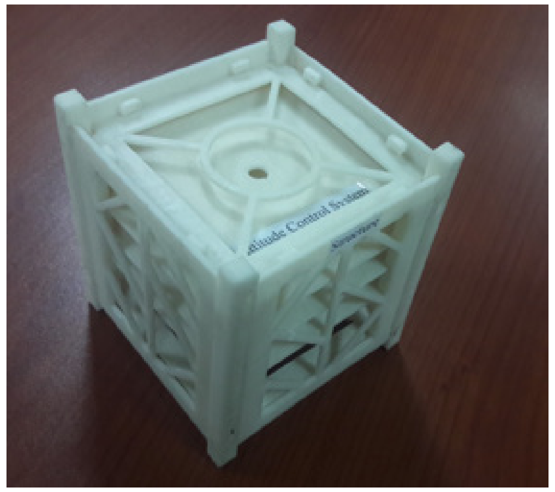


Fig. 11. A 3D printed version of a 1U CubeSat

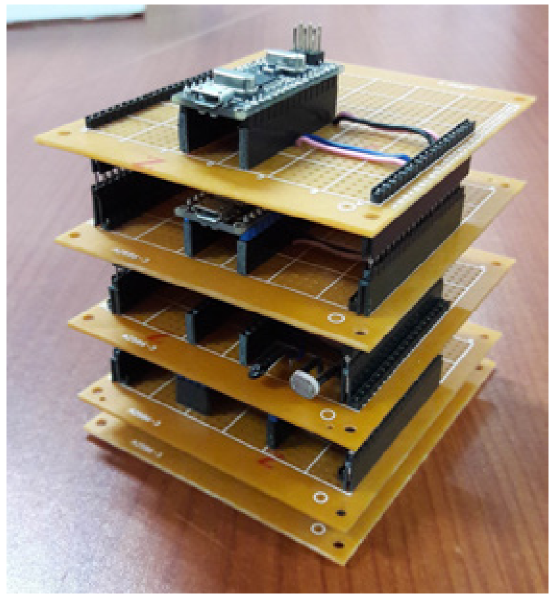


Fig. 12. Advances of the different modules of the UCHSat-1

3.2 Mission Parameters
For the mission, it is established that the region of interest in Peru since it is desired to take images of Peruvian territory for different applications. It will have the ground stations of Panama and Santiago de Chile, which are the closest, in support of the mission. In Figure 14, one can see a screenshot of the parameters of the mission simulation.

3.3 Simulation Parameters

For the final parameters of the simulation, a height of 400 km is established assuming that the UCHSat-1 could be launched from the International Space Station (ISS). The simulation is configured for the 2020 year and for only 1 day. In Figure 15, you can see a screenshot of the simulation parameters.

3.4 Visibility

In Figure 16, one can see the visibility results of the simulation. Taking into account the two selected ground stations, there is a total of 7 passes, 3 passes over the Panama ground station and four passes over the ground station of Santiago de Chile. The details of these passes can be seen in the Appendix A and Appendix B.

3.5 Parameter Values

In Figure 17, one can observe different results of the different nanosatellite parameters. One can see the consumption of the batteries, the generation of energy, the state of memory, the rate of data generation, and events. According to this information, it can be observed that the power generated is enough to feed the nanosatellite modules, among other aspects.

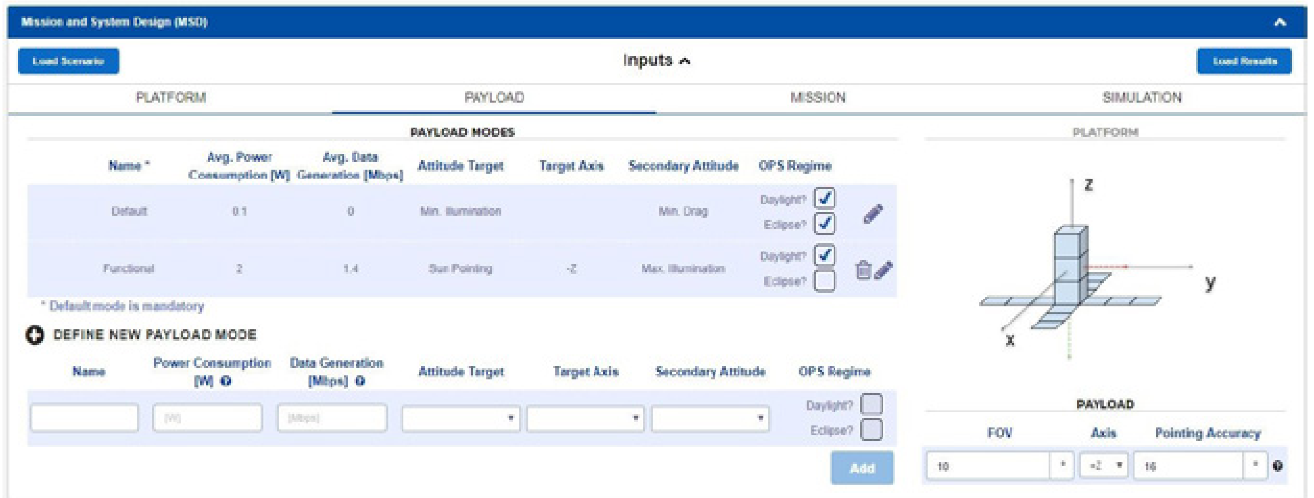


Fig. 13. Payload parameters for simulation

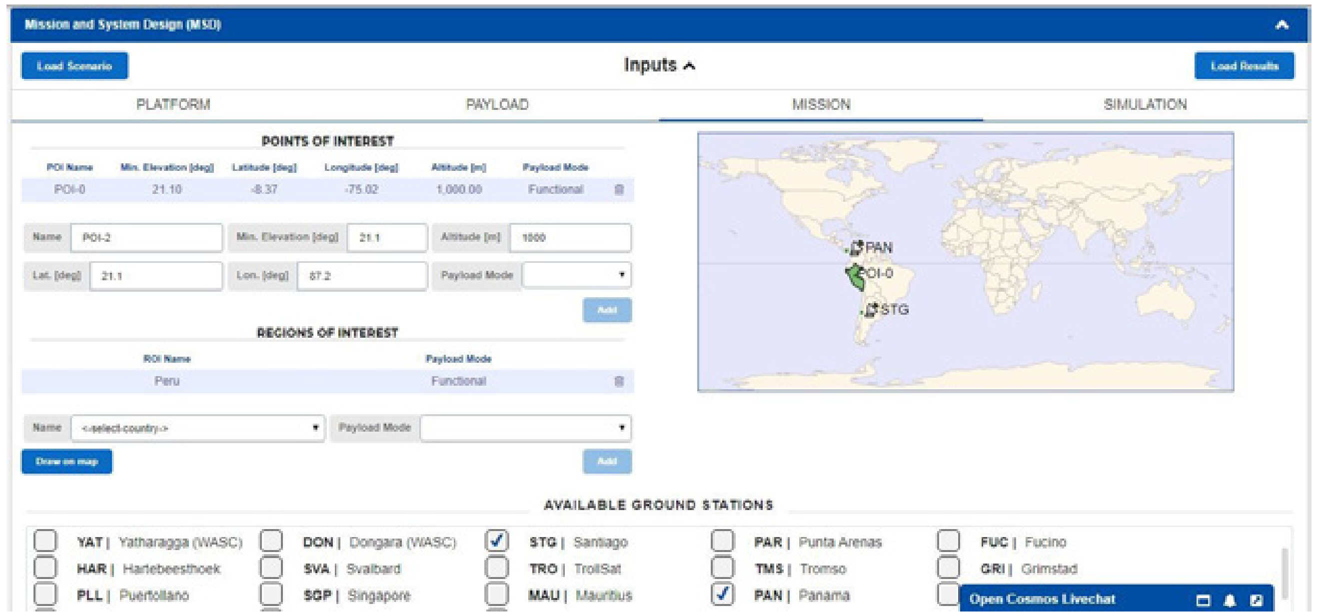


Fig. 14. Mission parameters for simulation

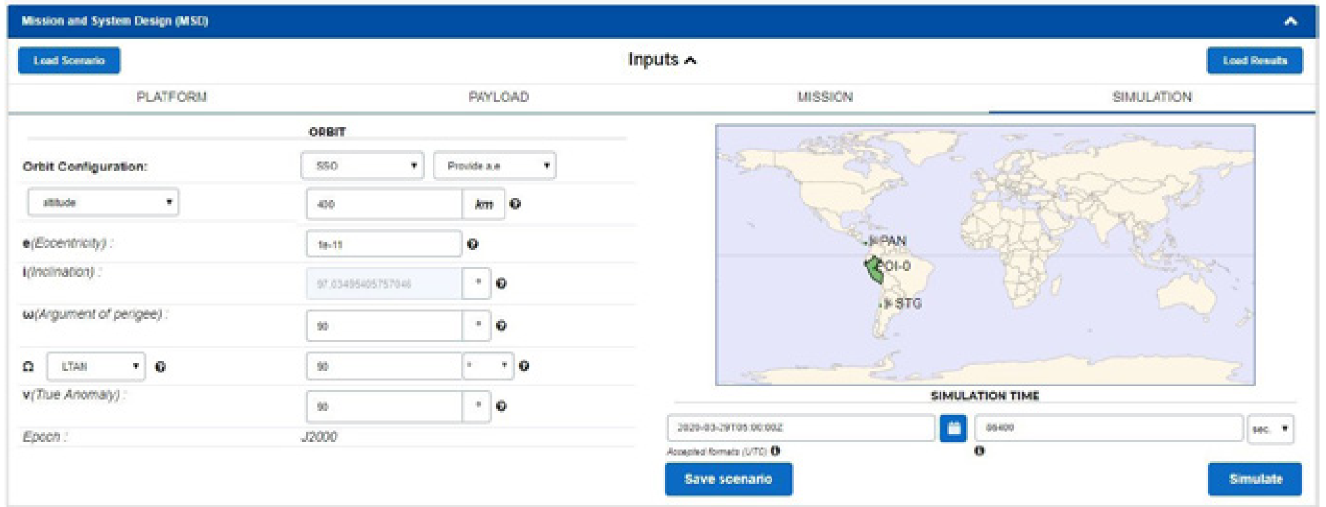


Fig. 15. Simulation parameters

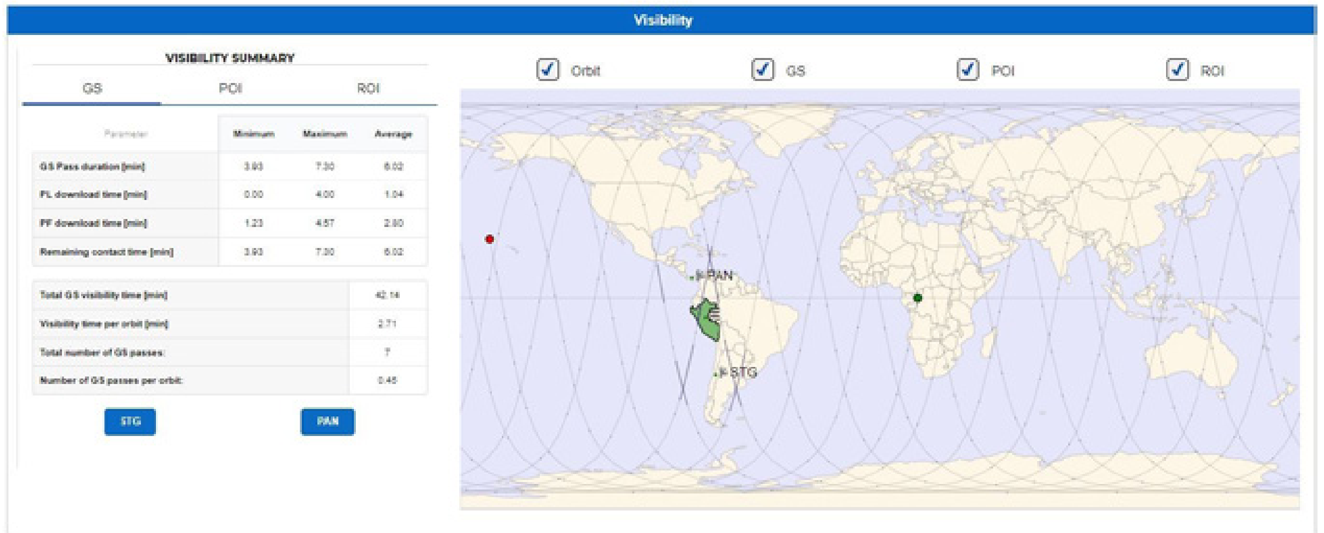


Fig. 16. Visibility simulation for the UCHSat-1

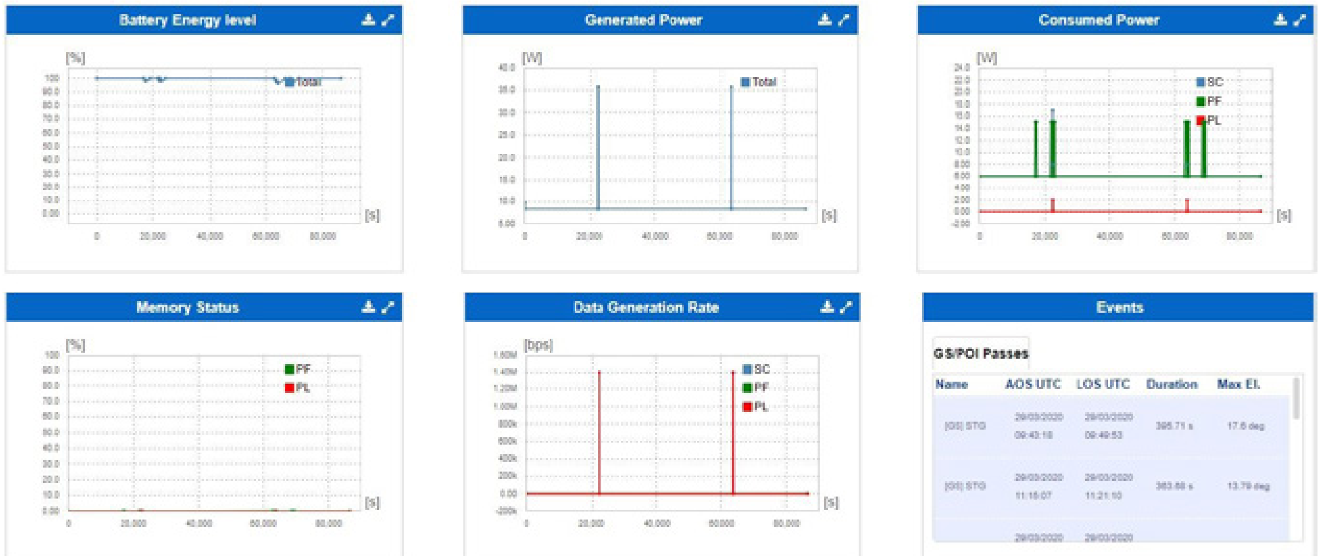


Fig. 17. Results of parameters simulation for the UCHSat-1

3.6 Events

As already mentioned, the UCHSat-1 during the simulation day will have seven contacts with the ground stations, 3 with Panama and 4 with Santiago de Chile. Likewise, UCHSat-1 will have 2 passes over the point of interest. The details of these 9 data are described in Table 3.

Table 3. Events: Ground Station and Point of Interest Passes

Name	AOS UTC	LOS UTC	Duration	Max El.
[GS] STG	29/03/2020 09:43:18	29/03/2020 09:49:53	395.71 s	17.6 deg
[GS] STG	29/03/2020 11:15:07	29/03/2020 11:21:10	363.68 s	13.79 deg
[GS] STG	29/03/2020 22:31:41	29/03/2020 22:38:55	434.30 s	25.51 deg
[GS] STG	29/03/2020 00:04:17	29/03/2020 00:09:00	283.43 s	9.44 deg
[GS] PAN	29/03/2020 11:04:21	29/03/2020 11:11:40	438.27 s	27.45 deg
[GS] PAN	29/03/2020 22:43:08	29/03/2020 22:49:25	377.26 s	15.93 deg
[GS] PAN	29/03/2020 00:15:44	29/03/2020 00:19:40	236.03 s	7.81 deg
[POI] POI-0	29/03/2020 11:10:12	29/03/2020 11:13:45	212.99 s	49.98 deg
[POI] POI-0	29/03/2020 22:40:57	29/03/2020 22:42:34	97.32 s	21.1 deg

4. Discussion and Conclusions

Although one does not have a nanosatellite implemented yet, it is progressing little by little with the design. It can be concluded that the COTS EEE components can be used in nanosatellite missions, reducing the cost of these.

Likewise, the simulation of the mission was achieved using the Open Cosmos beeApp tool. As a result of the simulation, it can be concluded that in 24 hours of simulation, the nanosatellite will have seven contacts counting with the ground stations of Panama and Santiago de Chile. Of the 7 connections, the minimum time will be approximately 3.93 minutes and the maximum time of 7.30 minutes. This situation yielded a total of 42.14 minutes of contact per day. With this contact time and the transmission rate of 1.4 Mbps, it is more than enough to transmit the pictures taken by UCHSat-1.

Several INTI-Lab members have passed through the development of the INCA program, including two researchers and ten students.

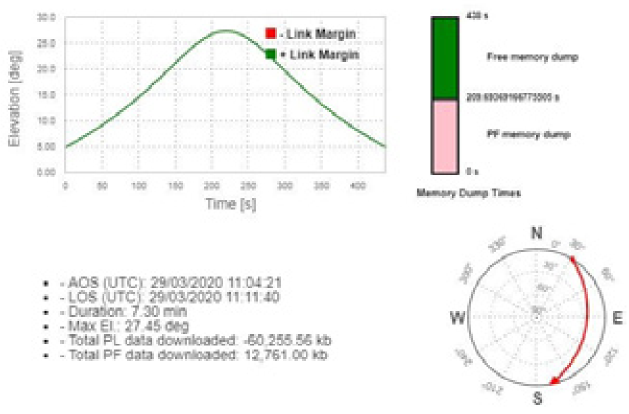
Part of the INCA program not only includes the nanosatellite but also applications with satellite images and the development of ground stations.

Acknowledgements

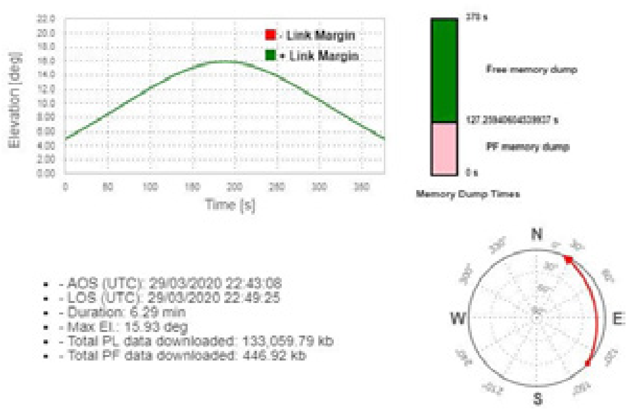
The authors wish to thank Open Cosmos (https://www.open-cosmos.com/) for allowing the use of its beeApp tool. It was possible thanks to the agreement signed between Open Cosmos and the Universidad de Ciencias y Humanidades.

Appendix A: Details of 3 Passes over the Ground Station of Panama

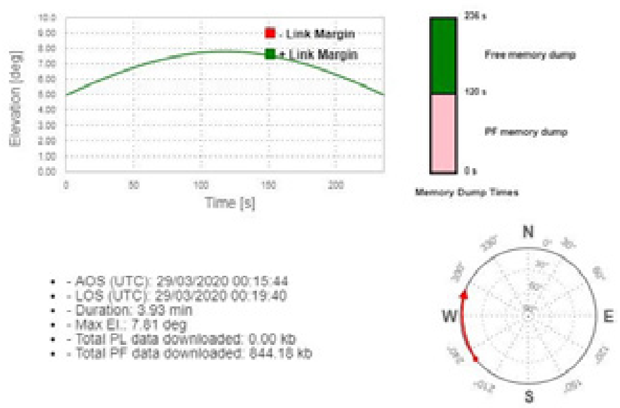
Pass 1



Pass 2



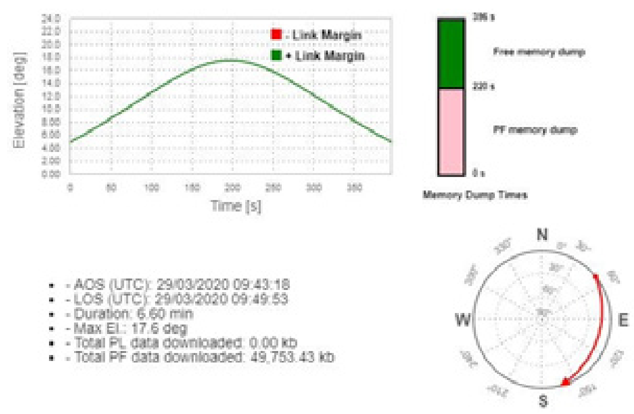
Pass 3



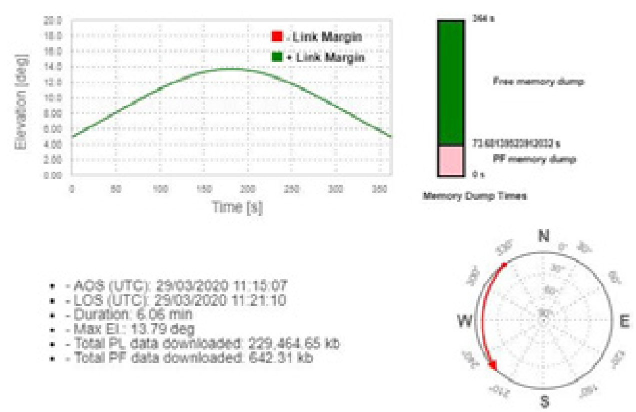
AD ASTRA – IAC Special Issue – 2019

Appendix B: Details of 4 Passes over the Ground Station of Santiago de Chile

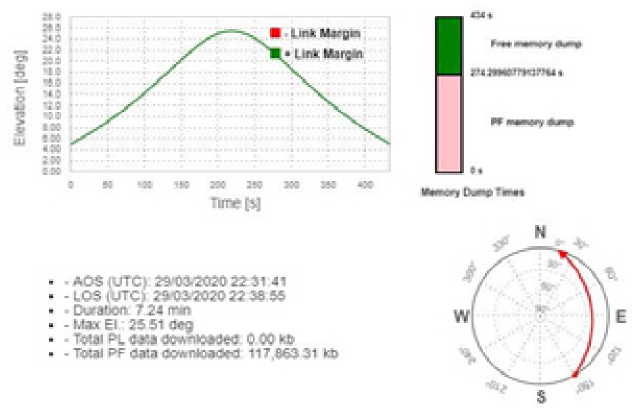
Pass 1



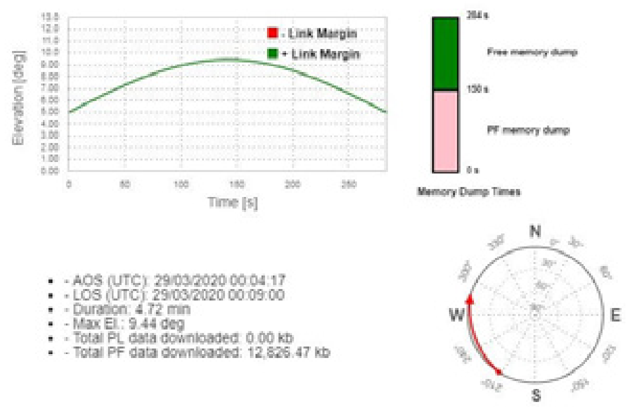
Pass 2



Pass 3



Pass 4



References

[1] Roman-Gonzalez, Avid, and Natalia Indira Vargas-Cuentas. “Aerospace technology in peru.” 66th International Astronautical Congress-IAC 2015. 2015.

[2] Postigo Diez Canseco, Diana Elena. “Diseño e implementación de un controlador de temperatura basado en el dispositivo Peltier para cámara ambiental en la prueba del satélite PUCPSAT-1.” (2011).

[3] Menéndez Quinto, Daniel Arturo. “Diseño e implementación del sistema de estabilización en el espacio para el picosatélite PUCP-SAT-1.” (2014).

[4] Vilchez Lagos, Neils Edison. “Diseño e implementación de un dispositivo de adquisición de imágenes para el PUCP-SAT1.” (2016).

[5] Montes Melgarejo, Raúl. “Diseño y manufactura de la estructura mecánica del primer nanosatélite peruano Chasqui I.” (2011).

[6] Espinoza Cárdenas, Antonino. “Diseño e implementación de un sistema de adquisición de imágenes para el nanosatélite Chasqui-I.” (2011).

[7] Quino Quispe, Gustavo. “Diseño y construcción de un generador de vibraciones aleatorias para las pruebas del nanosatélite Chasqui I.” (2013).

[8] Rojas Paredes, John Kerim. “Diseño e implementación de un sistema de adquisción embebido para su uso en la determinación de actitud del nanosatélite del proyecto Chasqui I.” (2015).

[9] Jara Alegría, Elvis Omar. “Diseño, simulación e implementación del módulo de control central y monitoreo de información de nanosatélite de investigación Chasqui-I de la Universidad Nacional de Ingeniería.” (2012).

[10] Marca, Juan, et al. “Investigación Satelital–UAPSAT.” Ciencia y Desarrollo 19.1 (2016): 7-23.

[11] López Aramburu, Fernando Maximiliano, and Martin Albino Solis Tipian. “Proyecto de investigación satelital-UAPSAT.” (2012).

[12] Villena de La Cruz, Giancarlo. “Implementación de un sistema en tiempo real embebido en la tarjeta del subsistema Command and Data Handling para incrementar la eficiencia del pico-satélite UAPSAT-1 de la

Universidad Alas Peruanas." (2014).
[13] Roman-Gonzalez, Avid, and Natalia Indira Vargas-Cuentas. "INCA PROGRAM FOR DEVELOPING A NANOSATELLITE AT THE UCH." 67th International Astronautical Congress-IAC 2016. 2016.
[14] Madeira, Henrique, et al. "Experimental evaluation of a COTS system for space applications." Proceedings International Conference on Dependable Systems and Networks. IEEE, 2002.
[15] Pignol, Michel. "COTS-based applications in space avionics." Proceedings of the Conference on Design, Automation and Test in Europe. European Design and Automation Association, 2010.
[16] Estela, Jaime. "COTS and the NewSpace." Radiation Effects on Integrated Circuits and Systems for Space Applications. Springer, Cham, 2019. 329-346.
[17] Konstantinidis, Kostas. "CubeSats: a Review." School of Electrical Enginnering, Democritus University of Thrace, Greece (2010).
[18] Romero-Alva, Victor, Witman Alvarado-Diaz, and Avid Roman-Gonzalez. "Design of a 3D Printer and Integrated Supply System." 2018 IEEE XXV International Conference on Electronics, Electrical Engineering and Computing (INTERCON). IEEE, 2018.

IAC-189,A6,IP,15,x49477

Preliminary Study of Aramid Fibre Cloth Removing the Space Debris

Fa-wei KE, Jie HUANG*, Xue-zhong WEN, Xin LI, Qiang SONG, Yao LONG, Sen LIU

Hypervelocity Impact Research Center, China Aerodynamics Research and Development Center, 2nd Ringroad 6, Mianyang Sichuan 621000, China , huangjie@cardc.cn
* Corresponding Author

Abstract

As the increasing space debris threatens the safety of on-orbit spacecraft, it is the current topic to remove the space debris. The aramid fibre cloth has good performance of intercepting the debris cloud, which has been used as the stuffed structure of space shield configuration. The study of aramid fibre cloth re moving the space debris cloud was carried out in the paper, and three fibre cloth intercepting structures are designed to intercept 5mm-dia meter aluminum projectile with the velocities fro m 3.2 km/s to 5.4 km/s. The first structure is the single layer of aramid fibre cloth. The second structure is several layers of aramid fibre cloths with some distance, and there is no stuffing between the cloths. The third structure is also several layers of aramid fibre cloths, and there is Al honeycomb between the cloths. There are several layers of Al plate placed after the intercepting structure, which are used to validate the cracking and decelerating of the projectile. The impact process is recorded by the self-developed sequenced shadowgraph instrument, which is mainly used to record the projectile integrity. The hypervelocity impact test results show that the aramid fibre cloth has the effect of intercepting and decelerating the projectile, which validates preliminary the feasibility of aramid fibre cloth being used to re move the space debris. In order to eliminate the effect of aramid fibre cloth cracking the projectile, it needs to optimize the thickness and distance of the fibre cloth.

Keywords: space debris, aramid fibre cloth, removal, hypervelocity impact, deceleration

Nomenclature

d = the diameter of the projectile (mm)
V = the impact velocity of the projectile (km/s)
$S1$ = the distance between the interception structure and the bumper (mm)
$S2$ = the distance between the two witness plates (mm)
$T1$ = the thickness of the first witness plate (mm)
$T2$ = the thickness of the second witness plate (mm)

1. Introduction

With the increase of human space activity, there are more and more space debris, which causes high threaten to the safe operation of the on-orbit spacecraft. Shielding and re moving the space debris have been the ma in study in the field of space technique for mo re than

10 years. In shielding filed, the ma in study works include developing new material and configuration with low a real density and high shielding performance, and many study results have been used in the improvement of the space shield. At present, the main possible methods of re moving space debris include laser energy [1-4], net [5-8], harpoon [8-11], robotics arm [12-16]. However, not a single space debris has been removed yet [17] according to the public reference. As space debris are moving with hypervelocity, it is very hard to re move them. In the space shield configuration, the stuffed aramid fabric has good performance of intercepting the debris cloud. The Ara mid-III cloth has been used on the shielding configuration of on-orbit spacecraft, and the PBO fibre has good performance of flame retardant. The Ara mid-III and the PBO with high tensile strength are chosen to decelerate and intercept the model with hypervelocity without damage in the paper, which also provides useful reference for re- recovering model [18, 19] and removing space debris.

2. Design of test target

There are three kinds of intercepting structures, and they are impacted with hypervelocity by the Al projectile . The first structure is the single layer of aramid fibre cloth. The second structure is several layers of aramid fibre cloths with some distance, and there is no stuffing between the cloths. The third structure is also several layers of aramid fibre cloths, and there is Al honeycomb between the cloths, which plays the role of bracing fib re cloth. When the model with complicated contour impacts the fibre cloth, the interaction force on the model may be uneven. The model moving direction would be changed when it penetrates the cloth. However, the channel effect of the honeycomb may play the role of restricting the model moving direct ion. The areal densities are 320.5 g/ m^2 and 105 g/ m^2 for the Aramid-III cloth and the PBO cloth, and their thickness is 0.53 mm and 0.15 mm respectively. For the Al honeycomb core, its height is 20 mm, and its side length is 10 mm, and its areal density is 321.2 g/m^2.

When the projectile with hypervelocity penetrates the fibre cloth, it may be parceled by the fibre dust, and it is hard to observe the integrity of the projectile. The several layers of Al plates shown in Fig. 2 are fixed after the interception structure. The penetration hole on the Al plate can validate the integrity and the deceleration of the projectile. The parameters of the target configuration are shown Table. 1. All A l plates are 6061. The thickness is 1 mm and 2 mm for the bumper and the rear plate. The accessorial frame shown in Fig. 2 is used to fix the fibre cloth conveniently.

Table. 1 The parameters of the target configuration

Target	Interception structure	*S1*	*T1*	*S2*	*T2*
A01	—	—	0.5mm	10mm	0.5mm
A02	3layers of individual aramid-III cloths with the distance of 41 mm	41mm	1mm	20mm	1mm
A03	3layers of individual PBO cloths with the distance of 41 mm	41mm			
A04	5 layers of PBO c loths. There is Al honeycomb core between two cloths.	10mm			
A05	—	—			
A06	1 layer of PBO cloth	121mm			

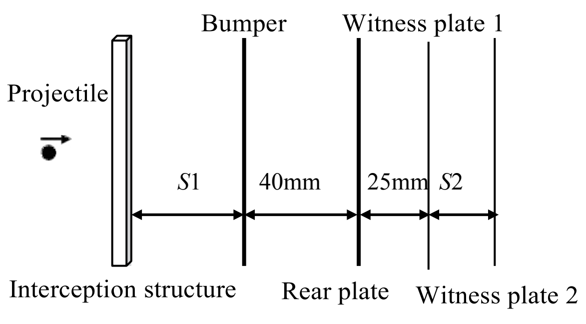


Fig. 1 The target sketch

3. Test equipment and measurement method

The tests of impacting the target with hypervelocity are finished on the HVI Range in China Aerodynamics Research and Development Center (CARDC). The HVI Range is equipped with two-stage light gas gun with the launching bores of 7.6 mm, and the maximum launching velocity is 8.7 km/s [20], and the maximum launching mass is 1.0 g. When the projectile flies through the chamber, the changes of its flying velocity can be ignored as the pressure in the chamber is lower than 50 Pa, and its average velocity is measured by the light screen system. The self-developed sequenced shadowgraph instrument [21] is used to obtain the shadowgraph images of the impact process.

The target damage is measured after the hypervelocity impact. The effect of fibre cloth intercepting and cracking the projectile is analyzed combining the target damage and the shadowgraph images of impact process.

4. The test results and analysis

4.1 The target damage

For target A01 (d=5.00 mm, V=3.28 km/s), the damage images of the bumper and the rear plate are shown in Fig. 2. The diameter of the penetration hole on the bumper is 7.80 mm. The big penetration hole of the rear plate is 16.5x11.6 mm, and the penetration holes are distributed in the range of ϕ65 mm, and the small bulges on the back are distributed in the range ϕ35mm. The projectile is intact before impact.

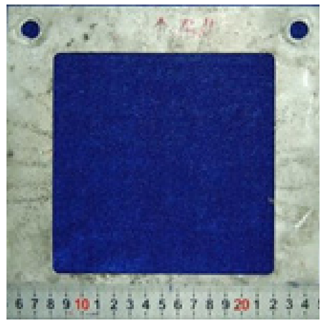
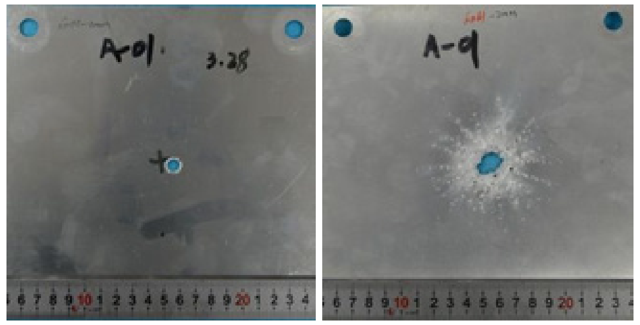


Fig. 2 The accessorial frame

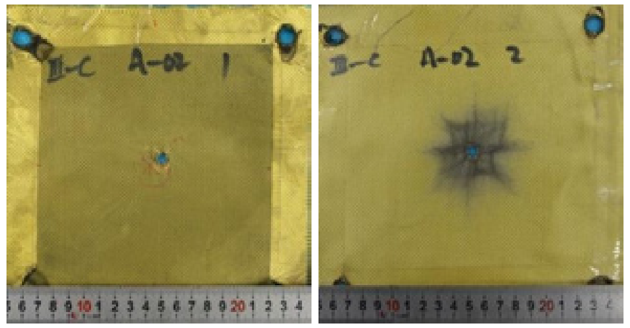


a. Face of the bumper b. Face of the rear plate

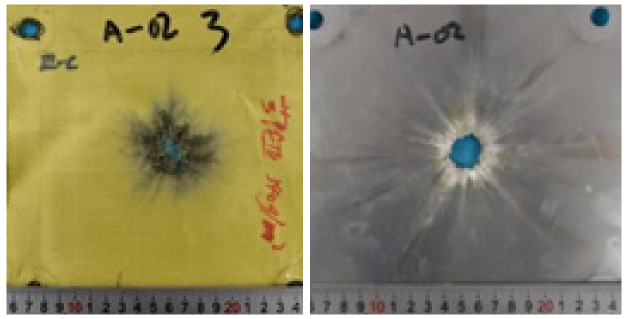
Fig. 3 Main damage images of the target A01

For target A02 (d=5.00 mm, V=5.42 km/s), the damage images of fabric cloth and the bumper are shown in Fig. 4. The penetration holes of the three layers of cloths are ϕ7.0 mm, ϕ9.0 mm, and 12.6x14.5 mm respectively, which a re increased gradually. The penetration hole on the bumper is 21.2x15.7 mm. The shadowgraph images of the impact

process are shown in Fig. 5. As the projectile is parceled by the dust when it penetrated the second and the third cloth, it is hard to judge the projectile integrity. However, the projectile has been cracked when it penetrates the third cloth according to the bumper damage.

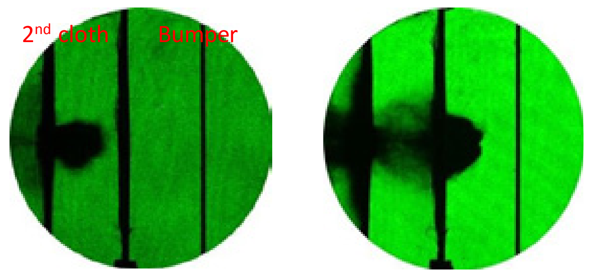


a. Face of the 1st cloth b. Face of the 2nd cloth



c. Face of the 3rd cloth d. Face of the bumper

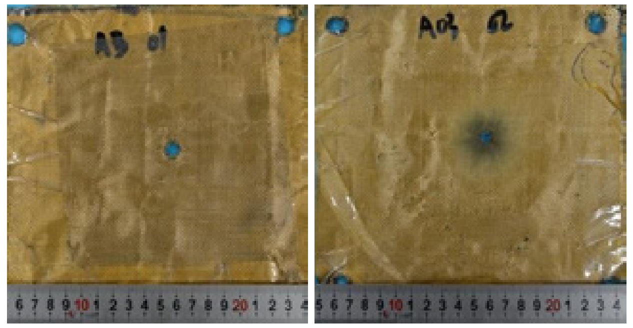
Fig. 4 Main damage images of the target A02



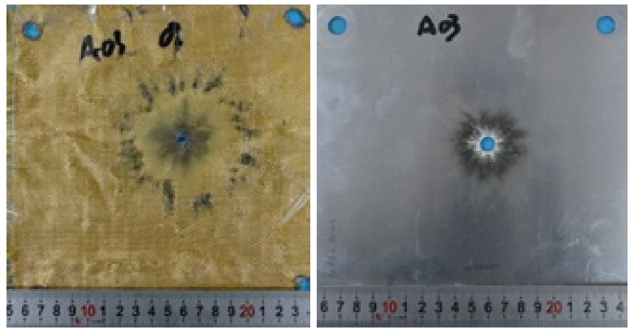
a. t=0 b. t=8 μs

Fig. 5 Shadowgraph image sequences of projectile impacting the target A02 (d=5.00 mm, **V**=5.42 km/s)

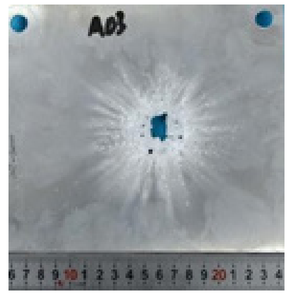
For target A03 (d=5.00 mm, V=4.28 km/s), the damage images of fabric cloth and the bumper are shown in Fig. 6. The penetration holes of the three cloths are ϕ9.0 mm, ϕ8.5 mm and ϕ8.0 mm respectively. And there are black dust distributed on the circular of ϕ70 mm for the third cloth. The penetration hole of the bumper is ϕ9.0 mm, and there are black dust distributed on range of ϕ45 mm. The big penetration hole o f the rear plate is 11.0x18. 0mm, and the penetration holes are distributed in the range of ϕ80 mm, and the small bulges on the back are distributed in the range ϕ42 mm. The shadowgraph images of the impact process are shown in Fig. 7. As the projectile is parceled by the dust when it penetrated the second and the third cloth, it is hard to judge the projectile integrity. However, the projectile may be still intact when it penetrates the third cloth according to the bumper damage.



a. Face of the 1st cloth b. Face of the 2nd cloth

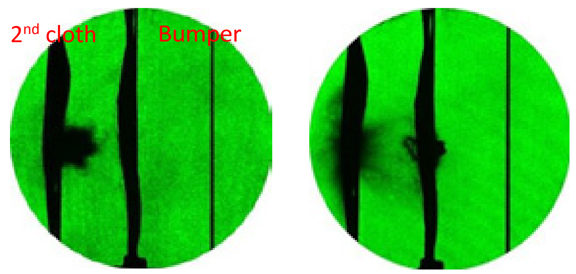


c. Face of the 3 cloth d. Face of the bumper



e. Face of the rear plate

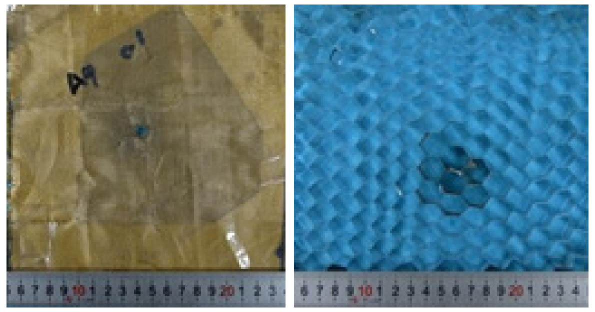
Fig. 6 Main damage images of the target A03



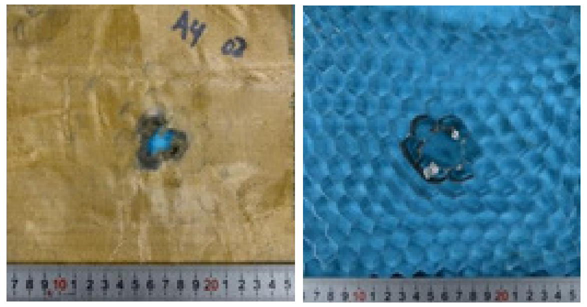
a. t=0 b. t=8 μs

Fig.7 Shadowgraph image sequences of projectile impacting the target A03 (d=5.00 mm, V=4.28 km/s)

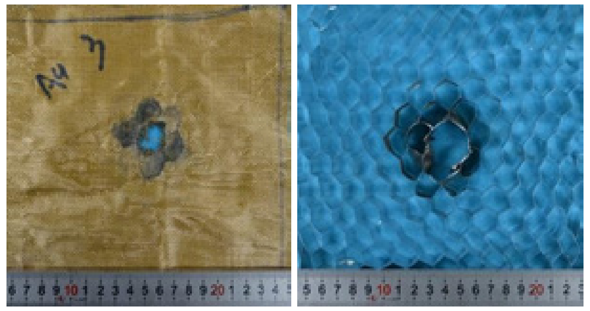
For target A04 (d=5.00 mm, V=4.19 km/s), the damage images of fabric cloth, Al honeycomb and the bumper a re shown in Fig. 8. The penetration holes of the five cloths are ϕ8.90 mm, 22x22 mm, 25x22 mm, 26x23 mm and 32x30 mm. The damage areas of the five honeycombs are ϕ34 mm, ϕ38 mm,ϕ40 mm, ϕ45 mm and ϕ65 mm. As the projectile impacts the interception structure, the penetration hole of cloth and the damage area of the A l honeycomb a re increased gradually. The bumper is penetrated with two holes of ϕ8.40 mm and ϕ5.50 mm distributed in the range of ϕ33 mm, and there are black dust distributed in the range of ϕ60 mm. The shadowgraph images of the impact process are shown in Fig. 9. According the target damage and shadowgraph images, the projectile is cracked when it penetrates the interception structure, and it may have been damaged when the projectile penetrates the first layer of Al honeycomb.



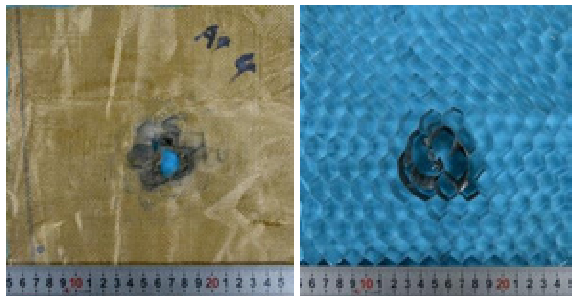
a. Face of the 1st cloth b. The 1st honeycomb



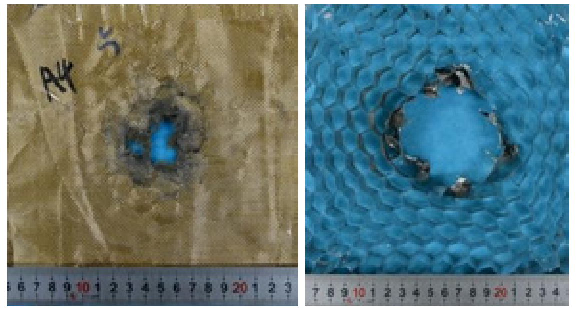
c. Face of the 2nd cloth d. The 2nd honeycomb



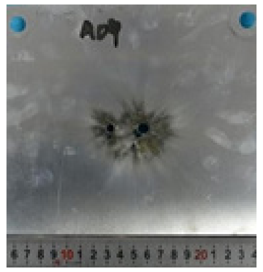
e. Face of the 3rd cloth f. The 3rd honeycomb



g. Face of the 4th cloth h. The 4th honeycomb

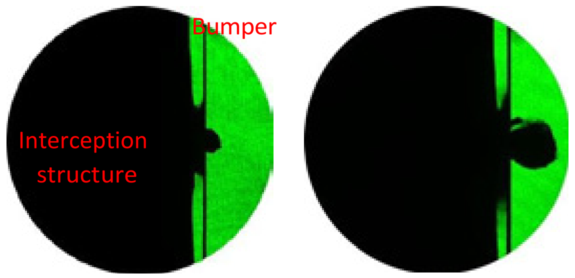


i. Face of the 5th cloth j. The 5th honeycomb



g. Face of the bumper

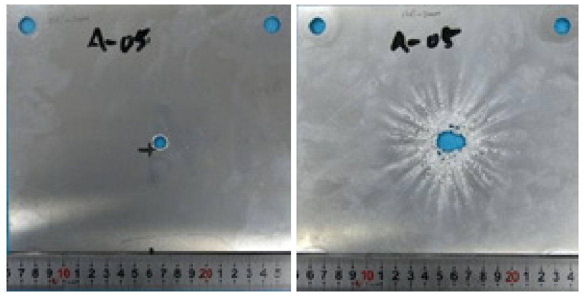
Fig. 8 Main damage images of the target A04



a. t=0 b. t=8μs

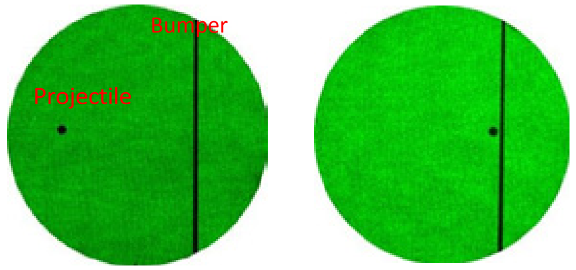
Fig. 9 Shadowgraph image sequences of projectile impacting the target A04 (d=5.00 mm, V=4.19 km/s)

For target A05 (d=5.00 mm, V=4.18 km/s), the damage images of the bumper and the rear plate are shown in Fig. 10. The diameter of the penetration hole on the bumper is 8.40 mm. The b ig penetration hole of the rear plate is 21.6x15.5 mm, and the penetration holes are distributed in the range of ϕ75 mm, and the small bulges on the back are distributed in the range 45x41 mm. The shadowgraph images of the impact process are shown in Fig. 11. According the target damage and shadowgraph images, the projectile is intact before impact.



a. Face of the bumper b. Face of the rear plate

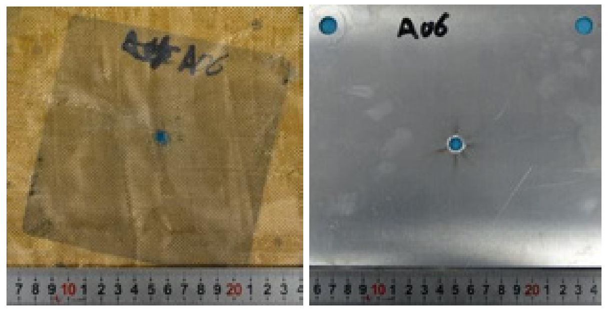
Fig. 10 Main damage images of the target A05



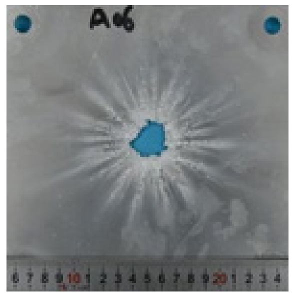
a. t=0 b. t=8 μs

Fig. 11 Shadowgraph image sequences of projectile impacting the target A05 (d=5.00 mm, V=4.18 km/s)

For target A06 (d=5.00 mm, V=4.33 km/s), the damage images of fibre cloth, the bumper and the rear plate are shown in Fig. 12. The penetration hole o f the fibre cloth is 8.1x8.4 mm. The diameter of the penetration hole on the bumper is 8.65 mm. The big penetration hole of the rear plate is 25.8x25.5 mm, and the penetration holes are distributed in the range of ϕ77 mm, and the small bulges on the back are distributed in the range ϕ45 mm. The shadowgraph images of the impact process are shown in Fig. 13. The projectile is parceled by the dust when it penetrates the fibre cloth, and the parceling phenomenon is weakened as the projectile moving forward. According the target damage and shadowgraph images, the projectile is intact when it penetrates the fibre cloth.

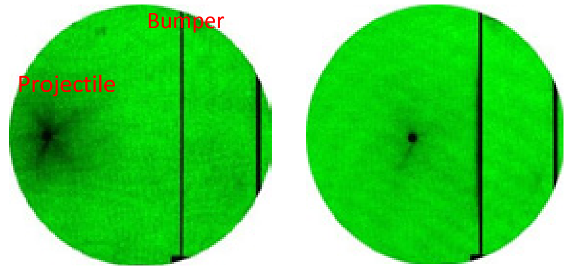


a. Face of the fibre cloth b. Face of the bumper

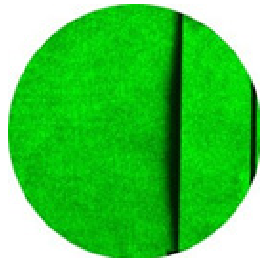


c. Face of the rear plate

Fig. 12 Main damage images of the target A06



a. t=0 b. t=8 μs



c. t=16μs

Fig. 13 Shadowgraph image sequences of projectile impacting the target A06 (d=5.00 mm, V=4.33 km/s)

4.2 Discussion and analysis

According to the target damage images and the shadowgraph image sequences of impact process, aramid cloth is one effective method to decelerate the projectile and keep its integrity. The backward load on the projectile can not exceed 10% o f the forward load during the process of decelerating and re-covering the model with hypervelocity. When the thickness of the fibre cloth attains the certain value, the interaction time between the model and the fibre is long enough to crack the model. There fore, the fibre cloth thickness and their distances should be optimized according to the model size and moving velocity. When contact method is used to re move the space debris, it may generate the secondary debris during the hypervelocity contact, which should be mainly considered and eliminated.

The projectile is parceled by the dust when it penetrates the fibre cloth, and it is hard to justify the projectile damage in the shadowgraph image. The vision image may justify the projectile damage. As the big distance between the fibre cloth, it needs big space to fix the m. The ballistic range of CA RDC has the 200m- long chamber [22], and the equipped two stage light gas gun can launch the model to hypervelocity, and the equipped shadowgraph imaging system and vision measurement system [23] can be used to record the process of model penetrating the cloth. Meanwhile , the equipped measuring velocity system can obtain the velocity change of the fibre cloth on the model. The relative work will be carried out.

The Al honeycomb placed between the cloths plays the role of bracing and restricting deform on the fibre cloth, which increases the rigidity of the fibre cloth and the effect on the projectile . When projectile impacts at the acme of the honeycomb core, the projectile will be incised and cracked [24]. The improvement on the assembling structure of the fibre cloth will be carried out.

5. Conclusions

The hypervelocity impact test results show that the ara mid fibre cloth has the effect of intercepting and decelerating the projectile with hypervelocity. The feasibility of using the aramid cloth to decelerate and intercept the debris cloud is validated preliminarily. The study results provide useful reference for capturing the space debris, decelerating and intercepting model with hypervelocity. In the future, the thickness and the distance of the fibre cloth, and their structure mode will be improved. And the relative study work will be carried out on the ballistic range.

Acknowledgement

The test is accomplished under the support of China space debris program (NO.KJSP2016030101). The special thanks should be extended to Wei JIANG, Wen-guang LI, Xiao-long LIU, and Jian-wen DING who have worked hard for the hypervelocity impact test.

References

[1] C. Phipps, G. Abrecht, H. Fried man, et al. Orion: clearing near-earth space debris using a 20-kW, 530-n m, earth-based, repetitive ly pulsed laser. Laser Part Bea ms, 14 (01) (1996)1-44.
[2] C.R. Phipps. A laser-optical system to re-enter or lower low earth orbit space debris. Acta Astronaut, 93(2014) 418-429.
[3] D. Liedahl, A. Rubenchik, S. Libby, et a l. Pu lsed laser interactions with space debris: target shape effects. Adv. Space Res, 52(5)(2013)895–915.
[4] J. Bennett, J. Sang, C. Smith, K. Zhang. Accurate orbit predictions for debris orbit manoeuvre using ground-based laser. Adv. Space Res, 52(11) (2013)1876-1887.
[5] B. Bischof, L. Kerstein, J. Starke, et a l., Roger-robotic geostationary orbit restorer. Sci. Technol. Ser. 109(2004)183-193.
[6] Shuang Wu, Fangli Mou, Qian Liu, et a l. Contact dynamics and control of a space robot capturing a tumbling object. Acta Astronautica, 151 (2018) 532-542.
[7] Minghe Shan, Jian Guo, Eberhard Gill. Contact dynamic models of space debris capturing using a net . Acta Astronautica, 158 (2019) 198-205.
[8] Jason L. Forshaw, Guglielmo S. Aglietti, Thierry Salmon, et al. Final payload test results for the Remove Debris active debris removal mission. Acta Astronautica, 138 (2017) 326-342.
[9] J. Reed, J. Busquets, C. White. Grappling system for capturing heavy space debris. Proceedings: 2nd European Workshop on Active Debris Removal, Paris, France, 2012.
[10] C. Billot, S. F rraris, R. Rembala, et al. E.deorbit: feasibility study for an active debris removal. Proceedings: 3rd European Workshop on Space Deb ris Modeling and Remediation, Paris, France, 2014.
[11] B. Robin, I. Luisa, E. Stephane, et al. The e .deorbit mission: results of ESA's phase a studies for an active debris removal mission. Proceedings: 66th International Astronautical Congress, Jerusalem, Israel, 2015.
[12] D. Reintsema, J. Thaeter, A. Rathke, et al. Deos the German robotics approach to secure and de-orbit malfunctioned satellites fro m low earth orbits. Proceedings of the i-SAIRAS, Sapporo, Japan, 2010.
[13] T. Boge, T. Wimmer, O. Ma, et al. Eposa robotics- based hardware-in-the-loop simulator for simulating satellite rvd operations. Proceedings of the 10th International Symposium on Artific ia l Intelligence, Robotics and Automation in Space (iSAIRAS), vol.29, Sapporo, Japan, 2010.
[14] T.J. Debus, S.P. Dougherty. Overview and performance of the front-end robotics enabling near- term demonstration (frend) robotic arm. Proceedings: AIAA Aerospace Conference, Reston, VA, USA, 2009.
[15] A. Ellery. Arobotics perspective on human spaceflight. Earth Moon Planet,s 87(3) (1999)173-190.
[16] P. Colmenare jo , M. Graziano, G. Novelli, et al. On ground validation of debris re moval technologies. Acta Astronautica, 158 (2019) 206-219.
[17] M inghe Shan, Jian Guo, Eberhard Gill. Rev iew and comparison of active space debris capturing and removal methods. Progress in Aerospace Sciences, 80(2016)18-32.
[18] PA N Xiaobin, NI Timin, TA N Leb in. High speed projectile soft recovery base on air damping. Journal of Vibration and Shock, 2016, 35(17): 77-82. (in Chinese)
[19] LU M ing, GU Wenbin, TANG Yong, et a l. Experimental research on high-speed EFP soft-recovery technology. Chinese Journal of Explosives and Propellants, 2008 31(5) 38-42. (in Chinese)
[20] Zou Shengyu, Li Xin, Luo Qing, et al. Momentum transfer measurements of hypervelocity impacts up to 8km/s by using ballistic pendulum. 6th IAA Planetary Defense Conference – PDC 2019, 29 April-3 May 2019, Washington, DC, USA.
[21] Ke Fa wei, Huang Jie, Song Qian, et al. Hypervelocity sequenced laser shadowgraph instrument and measurement of debris cloud with hypervelocity, Proceedings of the 2019 Hypervelocity Impact Symposium HVIS2019, April 14-19, 2019, Destin, FL, USA.
[22] Jiao De -zhi, Huang Jie, Ping Xin-hong, et al. Upgrading of 200 meter free-flight ballistic range at CARDC. Journal of Experimental in Fluid Mechanics, 2014, 28(2) 95-98. (in Chinese)
[23] Fawe i Ke , Jie Huang, Xin Li, et al. Vision measurement technique of model position and its widespread application on the ballistic range, Measurement, 140 (2019) 486-496.
[24] Huang Jie, Ma Zhao-xia, Lan Sheng-we i, et a l. Study on Hypervelocity Impact Characteristics for Honeycomb Sandwich with Multi-Layer Insulation. Journal of Astronautics, 31(8)(2010) 2043-2049.

IAC-19-C3 IP 8x54302

Prototype Solar Power Tower/ Advanced Heliostats and Build Sophisticated Transformers on Moon Surface

Sandhya Rao[a], Sreemon Chowdhury[b]

[a] *Technical Director, Notion Robotics Lab, New Delhi, India,* sandya.rao@notionrobotics.com
[b] *Electronic Engineer, Notion Robotics Lab, New Delhi, India,* sreemonchowdhury@notionrobotics.com

Abstract

During the recent times, the growth of the global interest in the space exploration of the surface of Moon/Mars is tremendous. With increasing advanced technology for planetary exploration, every mission including robotic exploration with landers, vehicles, spacecraft, rovers, space colonies and communication purposes are required an external power generation source and storage systems to fulfill the power requirements during space exploration missions. To ensure the continuous external power supply system on moon surface, Notion Robotics Lab has designed a prototype solar power tower and install a serial sophisticated solar powered Transformers of Heliostats and architecture for successive missions in the desired same region and for simultaneous powering of multiple platforms thus enabling to charge from the Heliostats. As procedures will be needed to combat the temperature differential that will occur on such a structure when exposed to sunlight on one end and the cold of deep space on the other. This prototype solar power tower will be equipped with autonomous system mounted with antenna mast and camera to support the system. This tower will be tall enough to receive sunlight continuously and therefore provide a continuous supply of electric power to lunar base. The research paper is in its initial development and presents an overall view of a new technology integrated summary of the Future Landers with Artificial Intelligence to address the challenge building of Lunar Transformers / Heliostats and to transform a region of an extreme hazardous environment into a friendly micro-environment/habitat, thus projecting solar energy at the location's where Robots or Human operate.

Keywords: - Prototype Solar Power Tower, Lunar Transformer, Autonomous Systems, Heliostats.

1. Introduction

Space exploration expands the envelope of human knowledge and presence throughout the solar system, and this process has been accelerated by a combination of human and robotic activities. With increasing advanced technology for planetary exploration, the next generation solar power system for Vehicles, Spaceflight, Lander's in outer space and earth, using prototype solar power tower and heliostats and storage systems, is becoming an essential requirement for any space mission.

During the recent times, the growth of the global interest in the space exploration of the surface of Moon/Mars is tremendous. Better understanding of the Lunar surface geology, geochemistry, morphology, geo-engineering and atmospheric science will provide more valuable insights to comparative planetary origins, the potential for past-present life and capabilities of the Lunar environment to sustain a long term robotic –human colonized habitat/ presence.

To design the Autonomous Robotic Rover with advanced Payloads /Instruments to bring in a new transformation in the region of Lunar and survive extreme space hazardous environment is the biggest challenge for the new space exploration. The main survival is to have a Power Generation, Power Houses/Transformer Heliostat Stations and Thermal Control as an ingredients that would allow the fleet of Robotic Rovers to cope with the Lunar Transformers. Using the resources, example harnessing the sun energy or using the Radioisotope Thermoelectric Generator (RTG). The main perspective and objective of this study is to have the advanced heliostat stations and to project solar energy to the precise locations around the autonomous fleet of rovers explorers , transforming it into a friendly survivable environment thus enabling us to give more experimental insights into future robot and human habitat.

In this Sections we provide different perspectives on notion rover, applications and directions of initial related development. Section 2 outlines the notion concept, general architecture , operational approach and deployment into future testing, Section 3 overviews the architecture, the software and functional organization of the rover.

2. Missions, Goals, Integrated Design of Autonomous Rover with the Prototype Solar Power Tower and Artificial Intelligence Software, TF Technologies

- Phase 1- To design and integrate with Neural Network/ Artificial Intelligence for path planning of Autonomous Robotic Rover System for Moon/Planetary Exploration.
- Phase 2- To design and develop the Prototype Solar Power Tower with Advanced Communication System to know the surrounded environments.
- Phase 3- To design, develop and install a Prototype of Serial Sophisticated Solar Powered Transformers of Heliostats and architecture for successive missions in the desired same region and for simultaneous powering of multiple platforms thus enabling the rovers to charge from the heliostats.

3. Construction of Autonomous Robotic Rover

3.1 Advanced Instruments System

-To examine and design a field Integrated Design and Operations Rover with robotic arm for Lunar Surface Exploration with advanced payloads thus able to satisfy the full set to target scientific exploration requirements with 300-310W of Power.

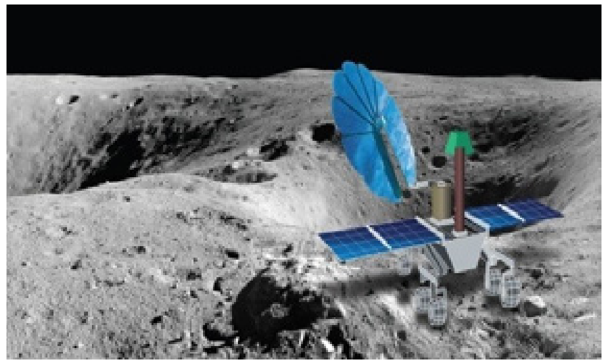


Fig.1. Notion Robotics Autonomous Robotic Rover

-Advanced instruments are selected as the payloads including Robotic Arm with advanced drill, 3D Panoramic Cameras, Ground Penetrating Radar IR Acoustic Spectrometer , X-ray Spectrometer, Engineering Cameras, Navigational Camera and Infrared Point Spectrometer, also a front mounted robot arm with multiple smaller instruments etc.

1. To develop 3D Cam and objective is to acquire 3D imagery of the lunar Surface for surveying the terrain, geographical features and structures, and craters inside the target region. It will also monitor the operational state of the Lander 2. The objective of the Ground Penetration Radar is to measure the lunar soil depth and the structural distribution of soil, magma ,lava tube and sub-surface rock layers 3. To use the Mast Cam, is stereoscopic camera system that will also have the ability to zoom in on interesting targets 4. To develop and sophisticated Alpha Particle X-ray Spectrometer and to measure the composition and distribution of various elements on the lunar surface by observing the scattered X-rays from the bombardment of alpha particles on rocks 5. To develop Imaging Spectrometer to measure the composition and resources of the lunar surface via imaging and spectrometry in the visible and near-infrared wavelengths.

-To adapt an new approach Notion Planner for long -range planetary navigation that bridges the gap between path planning and classical planning. Notion Planning calls upon the Incremental Search Engine (ISE) to enable heuristic path planning and efficient re-planning.

-To study the topography of the Shackleton crater, karst, cave etc.

3.2 Rover Concept and Testing Notion

Notion is a technology integration and mission simulation tested for semi-autonomous in situ science exploration. The usual operational paradigm for this class of rover is as follows: Based on down-linked panoramic imagery, as obtained from a rover-mounted camera's, notion scientists designate nearby targets of interest to which the rover navigates via intermediate way-points. These are designed ground coordinate locations, as referenced to the rover world frame and/or features autonomously recognizable by on-board sensing (information which taken together constitute part of trajectory sequence planning). The rover visually detects and avoids local obstacles en- route, while updating absolute trajectory coordinates. Rover localization over short distances is projectable from on-board odometry and inertial measurements; an extended traverse is referenced to sun-sensor absolute heading. Either source can be supplemented by visual terrain tracking/matching. In any case, it is usual and safe practice to confirm a hypothesized rover position by ground analysis—contrasting latest rover downlink imagery with an expected position (re-initializing local position in a larger panorama, setting as needed new local coordinate frame references for science activities).

This rover weighs approximately 140 to 160 Kilograms including a payload mass of 20 Kilograms and solar power tower weight approximately 30 to 40 Kilograms. It features a mast that facilitates the vehicle's stereo and navigation cameras and communication antenna, standing about 1.50 meters tall. The rover body is rectangular cuboids that feature solar panels and a robotic arm that holds part of the instrument payload. The rover is expected to survive three months in the harsh environment on the lunar surface – three lunar days & nights.

3.3 Power & Thermal Control System

The rover uses two rectangular solar panels that are locked on the top deck of the rover for launch and descent and deploy shortly after landing. Using the panels to generate electrical power, the rover operates throughout the two weeks of lunar day and charges its battery to survive the long lunar night. In its Lunar-Night-Sleep Mode, the rover is powered down to a large extent, only running core functions such as health monitoring and powering survival heaters.

The Rover carries Radioisotope Heater Units distributed throughout the vehicle to keep critical components at acceptable temperatures. RHUs unlike RTGs only provide thermal energy and no electricity. Using a small amount of a radioactive isotope (presumably Pu-238), the RHUs can provide about 1 Watt of thermal energy over a period of several decades. Typically, small RHUs weigh about 40 grams including shielding and are very compact in size, enabling them to be installed at various positions within a spacecraft for thermal control. The rover also uses passive thermal control featuring multilayer insulation to keep the vehicle from overheating in the sun.

3.4 Locomotion System

Notion rover uses a six-wheeled main- and sub-rocker-bogie suspension system similar to that used by NASA's Mars Exploration Rovers and Curiosity. The vehicle features rockers on each side of the suspension system that are connected to each other and the rover chassis through a differential. This technique allows the rover to maintain balance – when one rocker goes up because the vehicle driving over a small obstacle, the other side goes down. One end of a rocker is outfitted with a wheel while the other is pivoted to a bogie. This design allows the rover to climb over obstacles while keeping all six wheels on the ground. The tilt stability of the rover depends on the height of its center of gravity.

This six rover wheels are individually powered by six brushless DC motors. According to computer animations showing the rover, steering motors are used on the front and rear wheels which would allow the rover to turn in place. Each wheel has cleats that provide grip when driving through the fine lunar regolith. Rover can tolerate slopes of up to 20 degrees and drive over obstacles of up to 20 centimeters. Overall, the rover has been conceptualized for a total driving distance of up to 10 Kilometers.

4. Proposed Integrated Neural Network Model / Artificial Intelligence for Path-Planning of Autonomous Robotic Rover Systems for Moon/ Planetary Exploration

The advancement of robotics and space exploration in foray of technology that involves the manufacturing, design, and maintenance of robot machines that can operate in an autonomous robotic rugged design and can be used in a wide variety of applications including space exploration, weaponry, household, and transportation. The most sophisticated planetary rover which is a robot vehicle that moves across the surface of a planet and conducts detailed geological studies pertaining to the properties of the landing cosmic environment is designed developed by the Notions Computational Scientists. Rovers are always impeded by obstacles along the traveling path which can destabilize the rover's body and prevent it from reaching its goal destination. This paper proposes an ANN model that allows rover systems to carry out autonomous path-planning to successfully navigate through challenging planetary terrains and follow their goal location while avoiding dangerous obstacles. The proposed ANN is a multilayer network made out of three layers: an input, a hidden, and an output layer. The network is trained in offline mode using back -propagation supervised learning algorithm. A software-simulated rover is developed and experimented and it revealed that it was able to follow the safest trajectory despite existing obstacles. As future work, the proposed ANN is to be parallelized so as to speed-up the execution time of the training process.

4.1 Artificial Neural Networks

Artificial Neural Networks or ANNs for short are very influential brain-inspired computational models, which have been employed in various areas such as computing, medicine, engineering, economics, and many others. ANNs are composed of a certain number of simple computational elements called neurons, organized into a structured graph topology made out of several consecutive layers and immensely interconnected through a series of links called the synaptic weights. Synaptic weights are often associated with variable numerical values that can be adapted so as to allow the ANN to change its behavior based on the problem being tackled.

Training an Artificial Neural Network is usually done by feeding the network's input with a pattern to learn. The network then transmits the pattern through its weights and neurons until it generates a final output value. Afterwards, training or a learning algorithm compares the produced output value to an expected output and if the error range is high, the algorithm marginally alters the network's weights so that if the same pattern is fed again to the network, the output error would be smaller than the previous iteration. This process gets repeated for many cycles called epochs using different set of input patterns until the network produces acceptable outputs for all inputs. This learning progression allows the network to identify many patterns and further generalize to new and unseen patterns. Such type of training is called supervised learning which uses classified pattern information to train the network in offline mode. On the other hand, there exists what so called the unsupervised learning which uses only minimum information without pre-classification to train the network while being in online mode. Some of the most successful supervised learning approaches are feed-forward and back- propagation; while, the most successful unsupervised learning approaches are the Hebbian and the competitive learning rule.

4.2 The Proposed Artificial Neural Network (ANN) Model

This paper proposes an Artificial Neural Network (ANN) model for robotic planetary rover systems to accomplish path-planning on harsh and bumpy terrains. Its aim is to let the rover vehicle navigates through and follows its intended goal location while avoiding collisions with obstacles, rocks, holes, and sharp slopes of arbitrary shape and size. The movement of the rover is fully autonomous as it is totally controlled by the neural network without any human assistance except when training the network in offline mode.

The proposed ANN is a three layers "2-3-2" network composed of an input, a hidden, and an output layer. The input layer is made out of 2 input source nodes x and y with two corresponding neurons which are physically fed by the rover's sensors. The hidden layer is made out of 3 neurons which receive input data from the input layer and multiply them by the values of the synaptic weights denoted by Wij and then forward the resulted values to the output layer. The output layer is made out of 2 neurons that are directly linked to the rover's motors which control its movement and its mechanical operation.

The employed activation function is Sigmoid for the hidden neurons; whereas, it is linear for the output neurons.

The synaptic weights range from W00 to W13 and they represent the interconnection between the different neurons of the network. Additionally, two biases are employed in the hidden and the output layers to regulate and limit the output of the network and they are denoted by b_h and b_o.

Formally, the proposed neural network can be defined as follows:

NN = {I, T, W, A } where I denotes the set of input nodes, T denotes the topology of the network including the number of layers and the number of their neurons, W denotes the set of synaptic weights values, and A denotes the activation function.

I ={x, y}

T = $\{L_{in-2}, L_{h03}, L_{out-2}\}$

WLin = $\{W_{00}, W_{01}, W_{02}, W_{10}, W_{11}, W_{12}, W_{20}, W_{21}, W_{22}\}$……………………………….(1)

Wh0-3 = $\{W_{00}, W_{01}, W_{02}, W_{03}, W_{10}, W_{11}, W_{12}, W_{13}\}$ A = $\{1/1+e^{-t}, 1\}$…………………..(2)

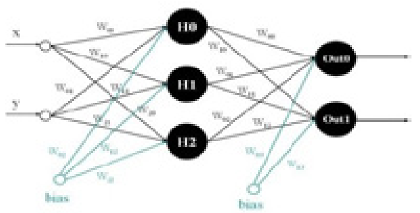


Fig.2. ANN Architecture

4.3 Advantages of ANN in Space Applications

Artificial Neural Networks have many ad vantages in space applications due to the following reasons:

1. Generally, a space rover system is required to process a very high number of parameters that are variable, complex, and received from multiple sources.
2. Neural Networks can handle such large-scale problems as it is able to classify objects well even when the distribution of objects in the *N*-dimensional parameter space is very complex.

Performance: Due to the nature of neural networks in executing in a parallel fashion, they can solve problems with multiple constraints and large number of data elements at high-speed and simultaneously. Using parallel technology, rover systems can increase their responsiveness and quickness in detecting, identifying, and handling new patterns behaviors.

Adaptability: Due to the dynamic and always-evolving conditions and challenges in space exploration missions, space rovers are always faced with new trends and patterns. Neural networks can cope with such circumstances as they are adaptable to unseen situations and have the capability to learn data, identify new patterns, and detect trends. A process that is too complex to be achieved by traditional computational techniques

Low Energy Consumption: Commonly, rovers are powered by solar panels which generate energy from light and photons particles, and then store it into internal batteries with limited lifetime and capacity. A supervised-trained neural network often learns and adjusts its synaptic weights in offline mode; thus, relieving the rover from carrying out insensitive mathematical computations at runtime and consequently reducing processing power, energy, and power consumption.

Robustness & Fault Tolerance: Since in a space applications a cosmic ray can be very destructive, it has however a little impact on neural networks as it can only destroy a few of the neurons, but not the thousands and the millions of neurons which would be able to compensate. For the damage and therefore the output of the network would not be significantly affected.

5. Proposed a Patented Prototype Solar Power Tower and Storage Systems to Fulfill the Power Requirements

5.1 Solar Power Tower (SPT)

Solar power towers (SPT), also known as central receiver systems (CRS), use a heliostat field collector (HFC), i.e., a field of sun tracking reflectors, called heliostats that reflect and concentrate the sun rays onto a central receiver placed in the top of a fixed tower. Heliostats are flat or slightly concave mirrors that follow the sun in a two axis tracking. In the central receiver, heat is absorbed by a heat transfer fluid (HTF), which then transfers heat to heat exchangers that power a steam Rankine power cycle. Some commercial

tower plants now in operation use direct steam generation (DSG), others use different fluids, including molten salts as HTF and storage medium. The concentrating power of the tower concept achieves very high temperatures, thereby increasing the efficiency at which heat is converted into electricity and reducing the cost of thermal storage.

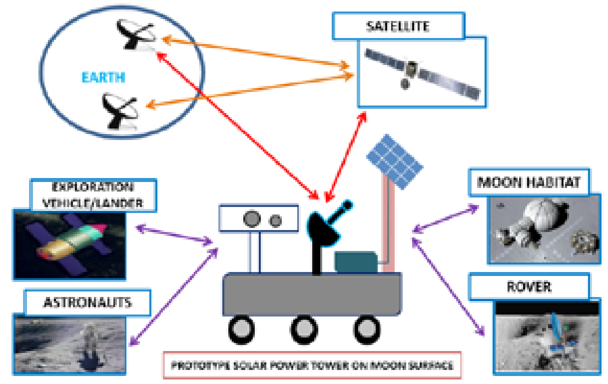


Fig.3. Prototype Solar Power Tower Integrating with Autonomous Rover

5.2 Microwave Beaming

Lunar Solar Power (LSP) arrays would receive higher energy density from sunlight. The key to lunar based solar to landers is microwave transmission. Energy from the sun can be converted into microwave in the same way radar beam generated.

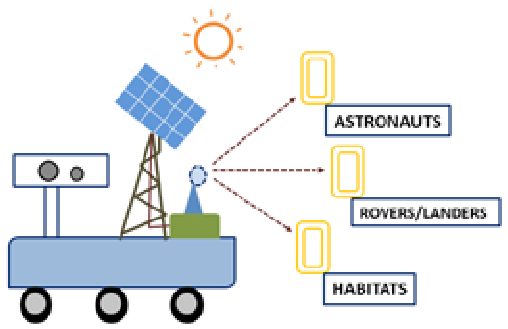


Fig.4. Power Transmission System

5.3 Battery

Notion Robotics Lab designed the Li-ion battery that stores energy. The way that it stores energy is by holding different electro-chemically active materials together is such a fashion so that they can generate and store free electrons (electrical potential energy) for long periods of time and only deliver that energy when the battery user demands it. The inherent properties of the electro-chemically active materials allow them to store energy chemically and then release that energy electrically as a bi-product of a chemical reaction.

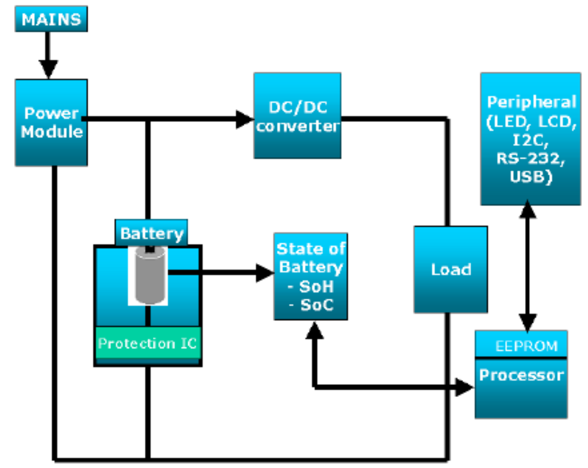


Fig.5. Battery Management System

5.4 Solar Panel

Notion Robotics Lab has designed thin solar panel (also solar module, photovoltaic module or photovoltaic panel) is a packaged, connected assembly of photovoltaic cells. The solar panel can be used as a component of a larger photovoltaic system to generate and supply electricity in commercial and residential applications. Each panel is rated by its DC output power under standard test conditions, and typically ranges from 100 to 320 watts. The efficiency of a panel determines the area of a panel given the same rated output - an 8% efficient 230 watt panel will have twice the area of a 16% efficient 230 watt panel. Because a single solar panel can produce only a limited amount of power, most installations contain multiple panels. A photovoltaic system typically includes an array of solar panels, an inverter, and sometimes a battery and or solar tracker and interconnection wiring. Solar panels use light energy (photons) from the sun to generate electricity through the photovoltaic effect. The majority of modules use wafer-based crystalline silicon cells or thin-film cells based on cadmium telluride or silicon. The structural (load carrying) member of a module can either be the top layer or the back layer. Cells must also be protected from mechanical damage and moisture. Most solar panels are rigid, but semi-flexible ones are available, based on thin-film cells.

Lunar Solar Power Tower System:

- Initial: 5kW to 10 KW
- Non-Nuclear/ Non-Mechanical
- Solar Cells

- Current technology: 300 W to 500 W/kg
- From 300 to 3000kg to transport lightweight cells
- High costs

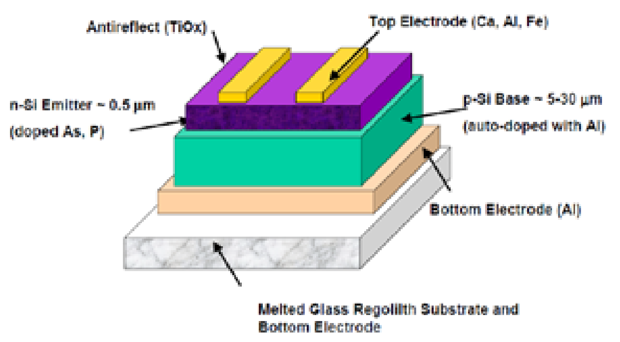


Fig.6. Lunar Silicon Solar Cell

There are many advantages of collecting solar power on the Moon rather than in orbit. First is saving the cost of launching tons of materials from the Moon and, perhaps more of a problem, catching the material in space. The work of processing and construction would be easier in the low gravity of the lunar surface than in zero gravity.

Even the problem of what to do with waste products is much easier on the Moon, as are the problems of housing and shielding workers.

6. Autonomous Rover Control & Navigation

This rover uses an onboard Delaunay algorithm that analyzes imagery acquired by the Navigation and Hazard Avoidance Cameras in real time using a stereo imagery analysis tool. This way, the rover is able to recognize obstacles and hazards that are automatically avoided. Furthermore, the rover is able to identify driving targets and autonomously plan the path towards the target location constantly determining its own attitude using its onboard sensors and identifying its relative position using real-time imagery.

Rover tele-operation from the ground is also planned to be utilized. The signal delay for a two-way trip from the Moon and back is 2.5 seconds allowing near real-time interactions with the rover and insight into its performance on the surface.

6.1. Multi Robot Distributed Control

We describe architecture for the development of autonomy software for multi-robot distributed control and collective estimation. That Control Architecture for Multi-Robot Planetary Outposts provides communication facilities for sharing of state information across robots and it uses a behavior network for representation and execution of group activities as well as the activities of a single robots.

6.2 Proposed Notion Software for Cooperative and Coordinated Activities:

Notion Software consists of a number of key mechanisms and architectural components that facilitate development of multi robot systems for cooperative and coordinated activities. These include the following:

1. Modular Task Decomposition: Following a behavior-based methodology, The Software provides fundamental building blocks for describing a system in terms of task-achieving modules known as a behavior-producing module or a behavior, for short. While a behavior provides a convenient and efficient architectural substrate to encapsulate perception and action, it is its interactions with other behavior-producing modules that generate the final behavior of the system. In its current implementation, task decomposition is done by hand and encoded in a script/plan, which is then executed by the agents. We are currently working towards extending with automated planning of joint team activities.
2. Behavior Coordination Mechanisms: A system's behavior is described as a network of behaviors that interact with each other and with the environment through sensors and effectors. The behavior interactions are regulated through behavior coordination mechanisms (BCMs). The BCMs are used to restrict and control the behavioral interactions so that the system can operate according to its specifications. In other words, the BCMs are used to ensure that the behaviors interact in a desired and consistent manner.
3. Group Coordination: The Software uses the same task decomposition scheme and representation to describe group activities, the deference being that the nodes (behaviors) of the network are distributed across the group of robots and connected through implicit (supported by extraprioceptive sensing) or explicit (radio) communication.
4. Communications Infrastructure: Relying on sensing for communication is not a feasible solution because sensing can be unreliable, the sensory envelope is often more range-limited than radio communication and it requires more computation for processing than is usually the case with radio communication.

The Software provides a software infrastructure that allows transparent inter-robot communication, which enables the robots to share state information, sensors, actuators, etc.

Future work developing control software for multi-robot systems using the conventional tools used for single-robot systems can become rather tedious and challenging. One challenge stems from the lack of access to the state of a multi-robot system, which is required for decision-making and control. Another challenge is the limitations of conventional representations for the description of group activities for a set of distributed entities with independent computing platforms. A related challenge is need for coordination of the activities of individual robots to accomplish a desired group activity. These are hard challenges for multi-robot, in particular for tasks which require tight coordination of activities and where the robots actions and states are interdependent. Our Software provides communication facilities for sharing of state information across robots and it uses a behavior network for representation and execution of group activities in the same way that it represents the activities of a single robot.

In our research, we have shown that Software almost bridges the gap between multiple robots and provides a level of abstraction that enables us to develop multi-robot software in a manner much similar to what we use for single robot software development. For future work, we are interested in further bridging this gap by extending Our Software with task planning capabilities and automation of group activity generation. Currently, we use Notion facilities to hand-craft the behavior network that represents a group activity. We are investigating approaches to automate this process so that behavior networks can be generated and implemented automatically.

7. Advanced Heliostats and Sophisticated Transformer

The biggest challenge is to build Lunar Transformers/ Heliostats and transform a region of extreme hazardous and severe environment into a favorable friendly microenvironment projecting energy at a specific location where robots operate for future missions.

Notion Robotics Lab have come up with a new design for concentrated Solar Power that reduces the required amount of land while boosting the amount of sunlight the heliostat mirrors collect. The most beautiful example of biomimicry yet, it's inspired by sunflowers and developed a computational model to evaluate the efficiency of heliostat layouts — the system divides each mirror into discrete sections and accurately calculates the amount of light each section reflects at any given moment.

The study formulates the new paradigm shift in the advancement of the concept. Advance the TF Concept with various studies and prototype of a mission scenario of Shackleton crater.

1. Focus on a polar volatile mission- to study and perform a detailed mission concept analysis, eliminate highest remaining risks. Increase TRL in various stages thus providing robustness solutions to radiation, dust meteorites, asteroids
2. 2Study the multi-hop reflections to project beyond line of sight thus enabling the light into caves thus helping controlled energy focus to reduce spill
3. Design study and scalability of the TFs unit with case histories of 1000m2 with a 100-micron and a weight of 8 -10 kg.

The micro-environment would have an advanced fleet of small rovers and proves with Artificial Intelligence with Neural imaging and would conduct a new series of experiments. The experiments would be building of a series of Heliostats or Lunar Transformers(LTs). Transformers are a class of Robotic Systems. They transform the environment /habitat of the region, and also adapt to the needs through functional and shape Lunar Surface embeds A) solar cells and batteries. B) Reflectors to redirect energy. C) Precisely redirect energy through actuation and control elements to change the shape and D) Computing.

The primary benefit of a TF is to make possible affordable missions that require survival for long periods of time without direct or with limited solar input. This way, environments without sunlight (such as craters and caves) can use TFs located in Sun-illuminated areas outside to project energy inside the permanently shaded areas, power solar panels, heat, illuminate, and relay communications. This report shows how a TF can be used in missions to lunar craters, lunar lava tubes, and Martian caves, relevant both for space science and for human exploration, TFs are the preferred solution for some missions and the enabling solution for new mission categories, in particular missions with multiple smaller rovers/probes, which cannot accommodate their own power/heating in the constrained size.

The concept and solutions for the Mission and the TFs can be used in missions to lunar craters lunar lava tubes, and caves which is relevant for Space Science/exploration and also for future human exploration. The multiple rovers is to build a multiple heliostats stations to direct the light to the lunar crater.

Fig.7. Advanced TFs and Heliostat Design for Crater Mission on the Moon

To perform a high level concept for Crater Missions on the Moon Shackleton Crater and a deep analysis of both mission trade-offs and also optical and thermal analyses for providing power for charging the solar panels and maintaining the rover warm while working to 30-80 k crater temperatures. To design different generation of rovers depending upon the study A rover with Notion technology is to able to satisfy the requirements of the full set of target scientific exploration with 250-300W of power. The small sized co-operative networked rovers would carry scientific payloads for different complex tasks. To embed the functions in-100 micron layers such that the weight is below 100 kgs and packs in less than 1 m3. To develop in built functions including pointing, sun tracking and a means to compute and actuate in the desired shape.

7.1 Heliostat and Field Layout

A single heliostat includes a set of mirrors, a tracking system, a frame, a structure foundation and control system. The heliostat turns so as to keep reflecting sunlight toward a predetermined target, compensating for the sun's apparent motions in the sky. The target may be a physical object, distant from the heliostat, or a direction in space. To do this, the reflective surface of the mirror is kept perpendicular to the bisector of the angle between the directions of the sun and the target as seen from the mirror. In almost every case, the target is stationary relative to the heliostat, so the light is reflected in a fixed direction.

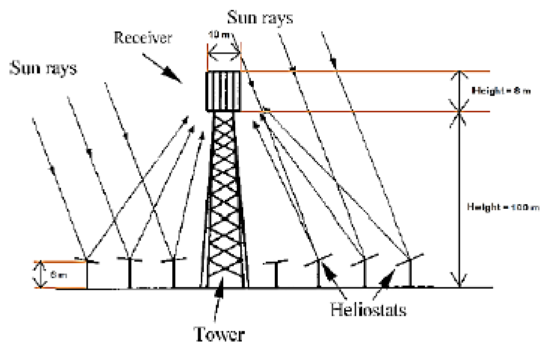


Fig.8. Solar Power Tower with Heliostats

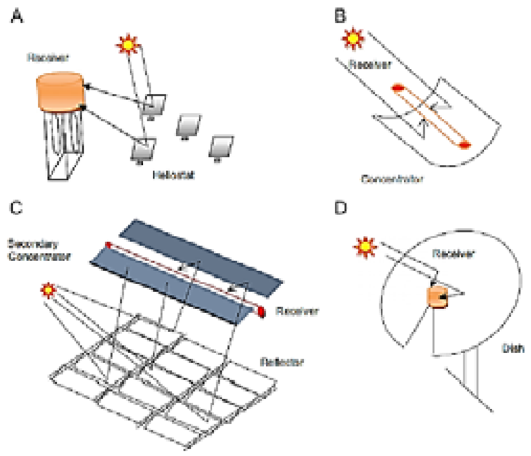


Fig.9. Heliostats System

Most modern heliostats are controlled by computers. The computer is given the latitude and longitude of the heliostat's position on the earth and the time and date. From these, using astronomical theory, it calculates the direction of the sun as seen from the mirror, e.g. its compass bearing and angle of elevation. Then, given the direction of the target, the computer calculates the direction of the required angle-bisector, and sends control signals to motors, often stepper motors, so they turn the mirror to the correct alignment. This sequence of operations is repeated frequently to keep the mirror properly oriented. Large installations such as solar-thermal power stations include fields of heliostats comprising many mirrors. Usually, all the mirrors in such a field are controlled by a single computer. The components of a heliostat are given below:

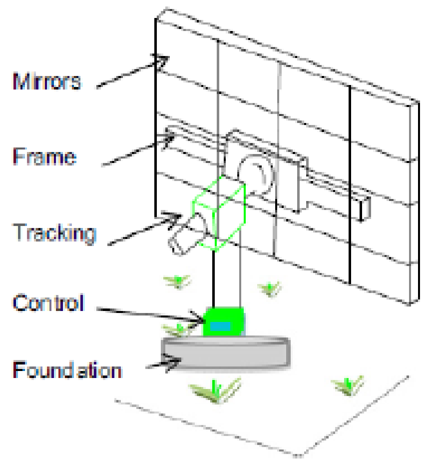


Fig.10. Architecture of Heliostat

Drive Components: These include azimuth and elevation gear, motor drives, and all linkages. Based upon the historical structural performance and costs for a heliostat system, the drive unit is both the main cost driver, as well as the most likely component to fail. In order to validate the design and derive a consistent and cost effective unit, the drive should be tested to the criteria in “Heliostats Design Optical Performance,” below. The drive system rated capacity should be based upon test rather than the manufacturer’s nominal catalog ratings.

Heliostat Structural Components: These include all mirrors support, the mirror attachment screws, the frames, the torque tubes, and the foundations, but exclude the drive mechanism. These items should be designed using loads from Peterka and Derickson (1992) and the standard building code factors of safety. Note that wind force levels W1, W2, and W3 are considered operating load cases so no increases in allowable stresses should be included. For the W4 wind loads, allowable stresses may be increased as permitted by the codes for short-term loads.

Tracking System: In the solar field, each heliostat tracks the sun to minimize the cosine effect, and therefore maximize the solar energy collection through positioning its surface normal to the bisection of the angle subtended by sun and the solar receiver. Heliostat sun tracking can be classified either as Open loop system or as closed loop system. The open loop system is based on astronomic formulae relating the sun’s position to the system geometry. This system is reliable-low cost and it is recommended for larger solar field because the heliostat is under computer control. On the other hand, the closed loop system uses sensor to track the sun. This system is then more accurate and very useful for small heliostat fields. However, this system suffers from lower performance during cloudy period. Two sun-tracking methods are usually applied in CRS, i.e., the Azimuth–Elevation (A–E) and Spinning–Elevation (S–E). Compared with A–E the S–E tracking method allows more solar energy collection at the receiver and reduces spillage losses by 10–30%.

AD ASTRA – IAC Special Issue – 2019

7.2 Heliostat Field

Heliostat field is the area surrounding the solar tower which has a number of heliostats placed in a predetermined manner. The best position for locating heliostats relative to the receiver and how high to place the receiver above the field constitute a multifaceted problem, in which costs and heliostat “loss” mechanisms are the variables. The layout of the heliostat field is an important aspect which decides the efficiency of the power plant. The main types of field layout are North-South radially staggered and surrounding type. In a North-South type layout, there are more number of heliostats placed on the northern side of the field. This is done to increase the thermal energy received on the central receiver. The radially staggered design helps in saving the losses caused by blocking and shadowing of the heliostats. In a surrounding type layout, the heliostats are placed on equal intervals and the number of heliostats to be placed in a particular row is calculated accordingly.

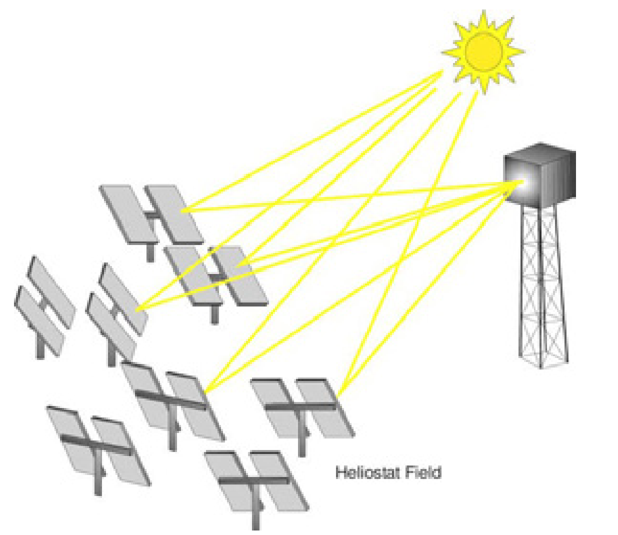


Fig.11. Heliostats Field

8. Research and Development

- Notion Robotics Lab has developed and plans to fly a small satellite about the size of a small cube that could help answer astrobiology fundamental questions about the origin, evolution and distribution of the life in the universe. We plan as secondary payload micro/nano-satellite, an innovative way to extend and enhance scientist’s opportunities to conduct research in low Earth orbit by providing an alternative to the International Space Station (ISS) or space shuttle investigations. With our payload we can analyse the stability of organics in the local space environment in real-time and test flight hardware that can be used for future payloads to address fundamental astrobiology objectives.
- We study the Solar Irradiance and Earth Radiation. The micro/nano-satellite aims at measuring on the same platform the absolute value of the Total Solar Irradiance (TSI) and its variability, and the different components of the Earth Radiation.
- -Critical components of instruments payloads of future large missions (coatings, UV filter etc.) also represent an excellent alternative for instrumentation testing.
- -This research paper is patented under Notion Robotics Lab.

9. Conclusions and Future Work

This paper presents an Artificial Neural Network model for robotic rover systems to perform autonomous path-planning during space exploration missions. The proposed ANN is a three-layer network composed of three layers: an input, a hidden, and an output layer. The network is trained through a supervised learning approach using the back-propagation algorithm. The purpose of the model is to control the movement of space rovers allowing them to travel across Lunar/ Planetary surfaces while avoiding obstacles in a complete autonomous manner. Experiments conducted showed that a software-simulated rover was able to avoid collision with obstacles and reached its goal location through the safe and correct trajectory.

As future work, the back-propagation algorithm, used in training the proposed network, is to be parallelized so as to take advantage of parallel and distributed computing platforms and speed-up the execution time of the training process.

Next generation Future Co-operative Robotic Rovers to carry on complete tasks from installation of Heliostats to Farming thus creating a Habitat of Autonomous Robots and Humans to colonize the Moon. To examine and design a Field Integrated Design and Operations Rover with robotic arm for Lunar Surface Exploration with Scientific Payloads thus able to satisfy the full set to target scientific exploration requirements with 300-310W of Power.

References:

[1] Amel Zerigui, Xiang Wu, Zong-Quan Deng, “A Survey of Rover Control Systems”, International Journal of Computer Sciences and Engineering Systems, Vol. 1, No. 4, pp. 105-109, 2007

[2] Roland Siegwart, Illah R. Nourbakhsh, David Scaramuzza, Introduction to Autonomous Mobile Robots, 2nd ed, The MIT Press, 2011.

[3] Jean-Claude Latombe, Robot Motion Planning, Kluwer Academ ic Publishers, 1991.

[4] Chowdhury, F.N., Wahi, P., Raina, R., Kaminedi, S., “A survey of neural networks applications in automatic control”, Proceedings of the 33rd Southeastern Symposium on System Theory, 2001.

[5] Paul J. Werbos, Beyond Regression: New Tools for Prediction and Analysis in the Behavioral Sciences, PhD thesis, Harvard University, 1974.

[6] Mars Exploration Rover, NASA Facts, National Aeronautics and Space Administration, Jet Propulsion

Laboratory, California Institute of Technology Pasadena, 2004.
[7] Deepak Bapna, Martin Martin and William Whittaker, "Earth-Moon Communication from a Moving Lunar Rover"
[8] Sarah Loff, NASA's Space Exploration Vehicle (SEV), NASA Official: Rocky Lind, 2011.
[9] Amy Svitak, "Cost of NASA's Next Mars Rover Hits Nearly $2.5 Billion." 2011, http://www.space.com/10762-nasa-mars-rover over budget.html.
[10] Wesley T. Huntress JR., Mikhail Ya Marov, Soviet Robots in the Solar System: Mission Technologies and Discoveries, Springer, 2011.
[11] Jun Wang, Xiaofeng Liao, Zhang Yi, "Advances in Neural Networks", Second International Symposium on Neural Networks, Chongqing, China, 2005.
[12] T.Ylikorpi *, G.Visentin **, J.Suomela *** "A Robotic Rover-Based Deep Driller for Mars Exploration", Proceedings of the 35th Aerospace Mechanisms Symposium, Ames Research Center, May 9-11, 2001.
[13] Avi B. Okon "Mars Science Laboratory Drill", Proceedings of the 40th Aerospace Mechanisms Symposium, NASA Kennedy Space Center, May 12-14, 2010.
[14] Dr. Robert A. Cassanova "BIO-NANO-MACHINES FOR SPACE APPLICATIONS
[15] Martin Anthony, Peter L. Bartlett, Neural Network Learning: Theoretical Foundations, Cambridge University Press, 2009.
[16] Edelson B.I. and Pelton J.E. (Eds.), "Satellite Communications Systems and Technology", International Technology Research Institute, JTECH/WTEC Program, Loyala College, Maryland, July 1993.
[17] A. Ignatiev and A. Freundlich, M. Duke, S. Rosenberg, "New Architecture for Space Solar Power Systems: Fabrication of Silicon Solar Cells Using In-Situ Resources", NIAC 2nd Annual Meeting, June 6-7 2000.
[18] Omar Behar a,*, Abdallah Khellaf b, Kamal Mohammedia, "A review of studies on central receiver solar thermal power plants", Renewable and Sustainable Energy Reviews 23 (2013) 12–39, journal homepage: www.elsevier.com/locate/rser.
[19] Kitsuregawa, T., "Advanced technology in satellite communication antennas: electrical and mechanical design", Artech House, Inc., Norwood, MA., 1990.

IAC-19-C4 IP 24x52877

Global Sensitivity Analysis of Parameters During Cure Process of SRM Composite Case

LIANG Qun[1], FENG Xi-ping[1], Li Jian[2], Chen Shu-hua[2], HOU Xiao[2]

(1. Science and Technology on Combustion, Internal Flow and Thermo-Structure Laboratory, Northwestern Polytechnical University, Xi'an 710072, China)
(2. The Fourth Academy of CASC, Xi'an 710025, China)

Abstract

The motor case for modern SRM is a complex compose structure with fiber reinforced resin matrix composite, EPDM insulation and metal connections, the case forming process is a multi physical-chemical process which involving heat transfer, chemical reaction and structure deformation. During the cure process, temperature determines whether the case cure completely and the uniformity of temperature field is an important factor in causing residual thermal stress and shrinkage stress, so temperature field is the key to the mutual coupling effect of each physical and chemical process, and the basis to analyze the cure process of the case. During the cure process of case, fluctuation of cure temperature, cure time or heat transfer of hot air in the furnace may occur, which make the actual forming process of case deviate from the ideal cure process. In order to investigate the sensitive degree of thermal cycle, convective heat transfer coefficient and thermal properties to cure uniformity during cure process of composite case, the influence rule of the three factors on uniformity of temperature and cure degree fields were analyzed by numerical simulation. A thermal-chemical model was built for a simplified composite SRM case firstly, and the model was verified. Then, the influence degree of the three factors on cure uniformity of composite case was analyzed and quantized by the Morris global sensitivity analysis method. The results show that he sensitivity order of the uniformity of temperature field for the four parameters is: thermal diffusion coefficient>heat transfer coefficient>duration time>cure temperature. Besides, he temperature and duration time of the fourth dwell stage have less effect on the cure uniformity of composite case than that of heat transfer coefficient. Therefore, it is a challenge to design a thermal cycle that can not only guarantee the vulcanization of EPDM insulation layer, but also improve the cure uniformity.

Key words: cure; cure degree; influencing factor; global sensitivity; Morris method; composite case; solid rocket motor

Introduction

Cure process is the key technology to composite manufacturing. The temperature change and distribution during cure process are determined by external heating and exothermic of cure reaction. However, thermal strain and cure shrinkage deformation will cause residual stress and deformation in composite, which may do damage to the quality of composite[1-4]. The gradient of temperature causes thermal strain and uneven cure, which leads to cure shrinkage, so the non-uniformity of temperature field and cure degree field of composite case during cure process is an important factor causing residual stress[5].

In order to probe into the changes of temperature of a composite laminate during cure process, Cheung et al [1]and Chen X B et al [6]have established a thermal-chemical coupling model which coupled the heat conduction equation and cure kinetics equation. Further, the cure reaction of resin leads to the change of the thermodynamics parameters of composite with the cure process, so a thermal- chemical coupling model has been established by Abdelal et al and Yuan Z. Y. et al, with consideration of the changing of thermodynamics parameters of composite during cure process to study the temperature change of composite structure during cure process [7,8]. Wang X. X and He J. L. have determined the order that parameter effects on the cure degree field of composite during the isothermal cure process by using the Morris method and the dimensional analysis method, respectively [9,10]. Wang J. M have put forward a method to optimize thermal cycle to improve the uniformity of temperature field and cure degree of composite during cure process [11]. However, there are few researches on quantitative analysis of the influence of cure parameters on cure process, most studies focus on qualitative analysis.

Sensitivity analysis method can study the sensitivity of a model to parameters. Morris method is a global sensitivity method, which is simple, easy to operate and calculate, it can analyze the influence of multiple parameters that change simultaneously in a large range on the model.

The manufacture of composite case has the characteristics of complex structure, mold and auxiliary, there is few studies about sensitivity analysis on cure process of SRM composite case. Based on the actual forming process of composite case, considering the mold and hot air flow in cure furnace, Morris method was used to quantify the influence of cure parameters on composite case cure process in this work.

1 Mathematical model for cure process

1.1 Thermo-chemical coupling model

The temperature distribution of composite not only affects the cure degree, but also determines whether the composite is uniformly cured, is the most direct cause of the residual stress of composite. The cure process is a process of chemical and physical reactions in anisotropic materials under external and nonlinear internal heat source, which is a thermo-chemical coupling process. The thermo-chemical coupling model are coupled of Fourier equation and the kinetics of cure reaction[12]:

$$\frac{\partial\left(\rho_c C_{p,c} T\right)}{\partial t} = \frac{\partial}{\partial x_i}\left(k_{ij}\frac{\partial T}{\partial x_j}\right) + \dot{q}_0 \tag{1}$$

$$\dot{q}_0 = \rho_r V_r H_u \frac{d\alpha}{dt} \tag{2}$$

Where ρ_c is the density of composite, $C_{p,c}$ is the specific heat capacity of composite, k_{ij} is the thermal conductivity of composite in three main directions, T is the temperature, t is the time, ρ_r is the density of resin, V_r is the volume of resin, H_u is the total heat released by cure reaction, α is the cure degree, which is obtained by the integral of instantaneous cure rate:

$$\alpha = \int_0^t \alpha' dt \tag{3}$$

and the internal heat source is directly related to the cure rate of resin.

1.2 Cure kinetic model

The cure kinetics of resin is generally expressed as[13, 14]:

$$\frac{d\alpha}{dt} = k(T) f(\alpha) \tag{4}$$

$$k(T) = Ae^{-E/RT} \tag{5}$$

Where $k(T)$ is the temperature dependent reaction rate function $K(T)$ can be expressed by an Arrhenius relationship, A is the pre-exponential factor which is the frequency of vibrations of the activated complex, E is the activation energy for the reaction, R is the gas constant, $f(\alpha)$ is the reaction mechanism function closely related to the cure degree, varies with resin types and cure conditions. According to the forms of $f(\alpha)$, cure kinetics can be divided into the following two categories:

(1) Nth order model
The maximum reaction rate occurs at the beginning of cure, which is the most prominent feature of the Nth order model, expressed as:

$$\frac{d\alpha}{dt} = k(1-\alpha)^n \tag{6}$$

(2) Autocatalytic model
The Autocatalytic cure reaction has an induction period, with the increase of cure degree, the cure rate speed first increases to the peak and then decreases, it generally expressed as:

$$\frac{d\alpha}{dt} = k(1-\alpha)^n \alpha^m \tag{7}$$

And the Kamal-Ryan Autocatalytic model expressed as:

$$\frac{d\alpha}{dt} = (k_1 + k_2\alpha^m)(1-\alpha)^n \tag{8}$$

1.3 Thermal-chemical strain model for composite

The increment of shrinkage strain, longitudinal thermal strain and transverse thermal strain of composite are defined as follows [14],

$$\Delta\varepsilon^c = \frac{-1+\sqrt{1+4\Delta\alpha V_{sh}^T/3}}{2} \tag{14}$$

$$\Delta\varepsilon_L^{th} = \alpha_L \Delta T \tag{15}$$

$$\Delta\varepsilon_T^{th} = \alpha_T \Delta T \tag{16}$$

where $\Delta\alpha$ is the increment of cure degree, V_{sh}^T the total volume shrinkage of composite with cured completely, α_L and α_T the longitudinal thermal expansion co-efficient and the transverse thermal expansion coefficient of the composite, respectively.
From Eqs. (14), (15) and (16), it is obvious that the inhomogeneity of temperature and cure degree is the main reason for the thermal stress and shrinkage stress during the cure process of composite.

2 FEM model for co-cure process of the case

2.1 Geometric model of composite case and material parameters

The experimental composite case structure is shown in figure 1, composed of composite press layer, composite case, EPDM insulation, sand mold, steel mandrel and aluminum joints. And the composite press layer provides pressure during co-cure process, which will be removed after co-cured. Parameters of experimental composite chamber and the kinetics parameters of resin see [], and the kinetics parameters of EPDM are shown as table 1.

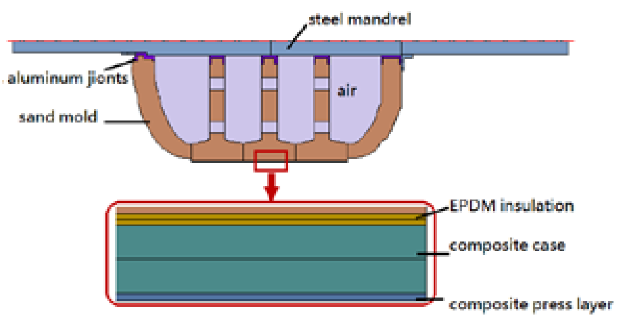


Figure 1. Experimental composite chamber structure

Table 1. Parameters of composite

Physical property	Value	
	Composite case	Composite press layer
$\rho(kg/m^3)$	1400	2081
$k(W/(m\cdot K))$	$0.00036(T-273.15)+0.19$	$0.00036(T-273.15)+0.20$
$C_p(J/(kg\cdot K))$	$6.8(T-273.15)+1000$	$7.8(T-273.15)+1000$
$H_u(J/g)$	217.8714	217.8714
$A(1/s)$	24902	24902
$E(KJ/mol)$	55.2683	55.2683
m	0.074	0.074
n	1.6362	1.6362

2.2 Validation of the co-cure model

In order to verify the correctness of the thermo-chemical coupling theory in the co-cure process of the composite chamber, the numerical simulation of the temperature field of the chamber's co-cure process is carried out, and the calculation results has been compared with the results of the co-cure experiment in previous work[15]. The maximum error between numerical calculation and experimental measurement is about 1.5%, therefore, it can be considered that the numerical simulation calculation is basically consistent with the actual measurement.

3 Global sensitivity analysis based on Morris method

3.1 Morris method

The Morris method was first proposed by Max D. Morris in 1991, which is a discrete search method based on parameter space, studying the impact on the system when multiple parameters of the model change simultaneously in a global scope. Suppose the model of system is: $y = f(x_1, x_2, \cdots, x_k)$, k is the number of influence factors. Mapping the variation range of each influence factor to the interval [0,1], then discretizing, so each influence factor can only be valued by $\{0, 1/(p-1), \cdots, 1\}$, p is the number of samples of each influence factor. The steps to analyze global sensitivity by using Morris method are as follows:

(1)Construct an m-by-k matrix(m=k+1):

$$B = \begin{bmatrix} 0 & 0 & 0 & \cdots & 0 \\ 1 & 0 & 0 & \cdots & 0 \\ 1 & 1 & 0 & \cdots & 0 \\ 1 & 1 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & 1 & 1 & \cdots & 1 \end{bmatrix} \tag{17}$$

The first row of the matrix represents the basic state of each influence factors, that is randomly valued by $\{0, 1/(p-1), \cdots, 1\}$. The rest rows determined all the influence factors, and '1' represent changing factors, '0' represent constant factors. There is only one element is different between any two adjacent rows in the matrix B.

(2)Input the elements of two adjacent rows into computational model separately, suppose there is only the elements in the j[th] column is different between the two rows:

$$B(j)=\begin{bmatrix} x_1 & x_2 & \cdots & x_i & x_j \cdots & x_k \\ x_1 & x_2 & \cdots & x_i & x_j' \cdots & x_k \end{bmatrix} \quad (18)$$

Define $\Delta = x_j - x_j'$, and $\Delta = 1/p-1$, so the influence magnitude of the j^{th} factor is:

$$E(j)=\left[y\left(x_1,x_2,\cdots,x_i,x_j,\cdots x_k\right)-y\left(x_1,x_2,\cdots,x_i,x_j',\cdots x_k\right)\right]/\Delta \quad (18)$$

(3)Due to the randomness of Morris method, it's easy to make errors in random sampling and randomization, so running r times of the step1 and step2 is necessary in order to reduce error.

(4)Calculate the average influence magnitude of r cycles.

(5)According the average influence magnitude, estimate the global sensitivity of each influence factors. The larger the average influence magnitude is, the more sensitive the influence factor to the computational model is.

3.2 Design of computational conditions

The motor case for modern SRM is a complex compose structure with fiber reinforced resin matrix composite, EPDM insulation and metal connections, the case forming process is a multi physical-chemical process which involving heat transfer, chemical reaction and structure deformation. During the cure process, temperature determines whether the case cure completely and the uniformity of temperature field is an important factor in causing residual thermal stress and shrinkage stress, so temperature field is basis to analyze the cure process of the case. During the cure process of case, fluctuation of cure temperature, cure time or heat transfer of hot air in the furnace may occur, which make the actual forming process of case deviate from the ideal cure process.

The cure reaction of composite case is accompanied with vulcanization of EPDM insulation layer(vulcanization of EPDM is not studied in this work), the peak temperature of cure reaction is about 130°C and the peak temperature of vulcanization reaction is higher than 160°C. Due to the large size the composite case is, and considering the temperature of cure and vulcanization, a thermal cycle consist of four heat rises, four heat dwells and two heat downs has usually been applied in the cure process of composite case, shown as Figure2.

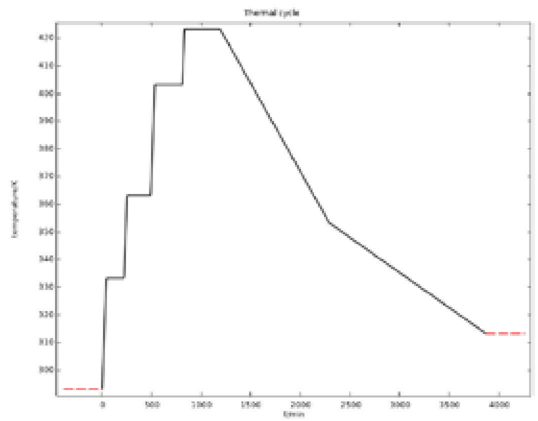


Figure2 Thermal cycle for composite case

Because the vulcanization of EPDM needs higher temperature, so usually more attention is paid to the temperature and duration time of the fourth dwell stage. Therefore, temperature of the fourth dwell stage and duration time of the fourth dwell stage are two influence factors for sensitivity analysis of composite case cure process. In addition, the convection heat transfer coefficient and the heat diffusion coefficient of composite also have certain effects on the cure process of composite case.
In the actual cure process, due to some man-made or environmental factors, the actual cure temperature, duration time and heat transfer coefficient may be somewhat different from the ideal process. Besides, the thermal diffusivity of composite may also different from the ideal one due to the deviation of the ratio of resin to fiber. In order to investigate the sensitive degree of temperature of the fourth dwell stage, duration time of the fourth dwell stage, convective heat transfer coefficient and thermal diffusivity to cure process of composite case quantitatively, the computational conditions are designed as table 2 and table 3, Where is the ideal thermal diffusion coefficient of composite.

Table 2. Four factors and corresponding levels used to analyze

global sensitivity of cure process of composite case

	level				
	0	1/4	2/4	3/4	4/4
cure temperature(℃)	140	145	150	155	160
duration time(hour)	6	8	10	12	14
heat transfer coefficient	8	12	16	20	24
thermal diffusion coefficient	0.8 α	0.9 α	α	1.1 α	1.2 α

Table 3. Computational conditions base on Morris method

Computational conditions	cure temperature(℃)	duration time(hour)	heat transfer coefficient(W/m^2)	Thermal diffusion coefficient(m^2/s)
1	140	6	8	0.8α
2	145	6	8	0.8α
3	145	8	8	0.8α
4	145	8	12	0.8α
5	145	8	12	0.9α
6	150	8	12	0.9α
7	150	10	12	0.9α
8	150	10	16	0.9α
9	150	10	16	α
10	155	10	16	α
11	155	12	16	α
12	155	12	20	α
13	155	12	20	1.1α
14	160	12	20	1.1α
15	160	14	20	1.1α
16	160	14	24	1.1α
17	160	14	24	1.2α
18	140	14	24	1.2α
19	140	6	24	1.2α
20	140	6	8	1.2α

4 Results and analysis

Based on the global sensitivity method, 5 Morris cycles were performed and 20 computational conditions were designed. Numerical calculation was carried out for the 20 computational conditions in table 3, and the variation of the unevenness of temperature field of the composite case with the cure process of each condition was obtained, as shown in Fig.3-7. From Fig. 3-7, it can be seen that the variation of unevenness of temperature field is similar and closely relate to the thermal cycle. That is, the unevenness of temperature field before temperature downs stage increases in the heating stage and decreases in the dwell stage, the maximum values of the unevenness of temperature field are reached at the end of heating stage and the minimum values of the unevenness of temperature field are reached at the end of dwell stage. in the initial of the first downs stage, the temperature of the outer case decreases with the decreases of the thermal cycle, while the temperature inside the case is still lower than the outside temperature, so the temperature inside the case continues to rise and the unevenness of temperature field decreases to 0 gradually. As the unevenness of temperature field reaches 0, the temperature of the outer and inner of the case is the same, then the inner of the case begins to cool down with the rate smaller than the outer, so the unevenness of temperature field increases gradually. As entering the second downs stage, the temperature drop rate of the outer of the case becomes slower, so the unevenness of temperature field decreases gradually. Although the variation patterns are similar, the value of unevenness of temperature field varies in each condition.

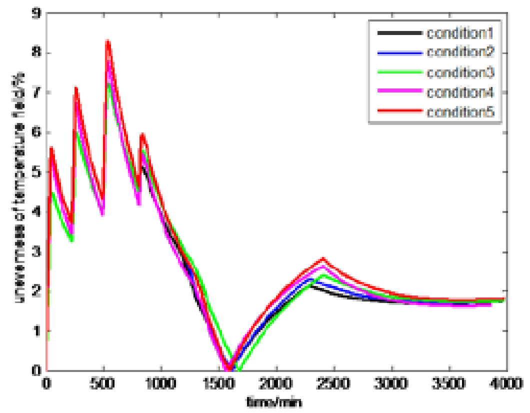


Figure 3 The first Morris loop

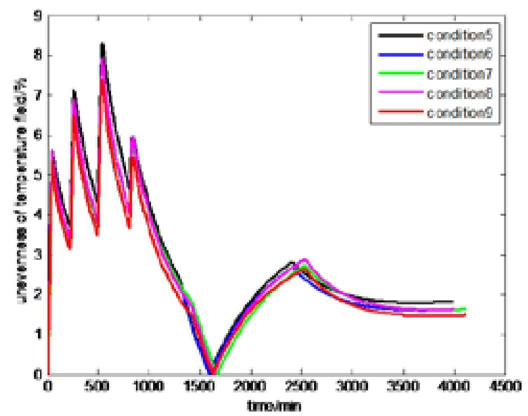


Figure 4 The second Morris loop

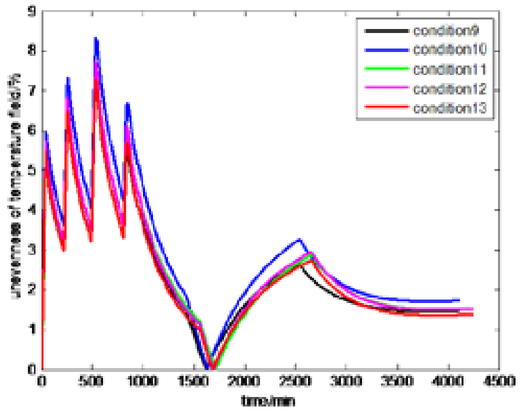


Figure 5 The third Morris loop

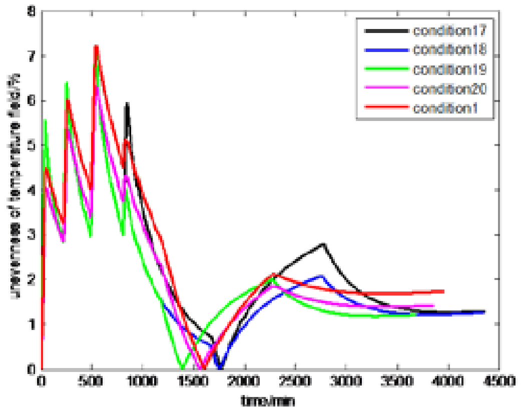


Figure 7 The fifth Morris loop

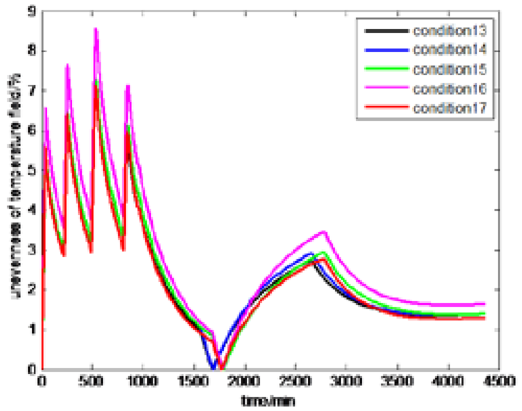


Figure 6 The fourth Morris loop

The global sensitivity calculation results of the composite case are shown in table 4. It can be found that the sensitivity order of the uniformity of temperature field for the four parameters is: thermal diffusion coefficient>heat transfer coefficient>duration time>cure temperature. It is worth noting that in the actual cure process, it's difficult for the thermal diffusion coefficient of composite to reach a deviation of 20%. Besides, it is found that the temperature and duration time of the fourth dwell stage have less effect on the cure uniformity of composite case than that of heat transfer coefficient. Therefore, it is a challenge to design a thermal cycle that can not only guarantee the vulcanization of EPDM insulation layer, but also improve the cure uniformity.

Table 4. Sensitivity degree calculation results of the uniformity of temperature field in composite case based on Morris method

	level					
	r=1	r=2	r=3	r=4	r=5	Mean
cure temperature	0	0.18	0.19	0	0	0.074
duration time	0	0	0.47	0.02	0	0.098
heat transfer coefficient	0.14	0.12	0.08	0.33	0.20	0.19
thermal diffusion coefficient	0.05	0.05	0.05	0.14	0.09	0.38

5 Conclusions

Based on the actual forming process of composite case, considering the mold and hot air flow in cure furnace, Morris method was used to quantify the influence of cure parameters on composite case cure process in this work. Some conclusions can be drawn as follows:

(1) The sensitivity order of the uniformity of temperature field for the four parameters is: thermal diffusion coefficient>heat transfer coefficient>duration time>cure temperature.
(2) The temperature and duration time of the fourth dwell stage have less effect on the cure uniformity of composite case than that of heat transfer coefficient

References

[1] CHEN Xiangbao, XING Liying, ZHOU Zhenggang. Simulation and modeling of polymeric composite temperature change during manufactory process[J]. Journal of Aeronautical Materials, 2009. 29(2) : 61-65.

[2] ZHANG Ji-kui, FU Guo-zheng, WU Lie-su, CHENG Xiao-quan. Residual stress induced by cure processing in thick section composite part: State-of-art[J]. Hi-Tech Fiber & Application, 2012,37(6):57-61.

[3] Yi S, Chian K S, Hilton H H. Nonlinear viscoelastic finite element analyses of thermosetting polymeric composites during cool-down after curing[J]. Journal of Composite Materials, 2002, 36: 3-17.

[4] Anxin Ding, Shuxin Li, Jiuxiao Sun, et al. A thermo-viscoelastic model of process- induced residual stresses in composite structures with considering thermal dependence[J]. Composite Structures,2016,136:34-43.

[5]Wang X X, Jia Y X, Cheng C, et al. Numerical analysis of curing reaction and demoulding deformation in resin transfer moulding processes[J]. Polymer Materials Science and Engineering, 2010, 26(9):151-154.

[6]Cheung A, Yu Y, Pochiraju Km Three-dimensional finite element simulation of cure of polymer composites. J. Finite Elements in Analysis and Design. 2004; 40(8): 895-912.

[7] Abdelal G F, Robotham A, Cantwell W. Autoclave cure simulation of composite structures applying implicit and explicit FE techniques[J]. International Journal of Mechanics and Materials in Design. 2013; 9(1): 55-63.

[8] Yuan Z Y, Zhu Y J, Zhang Y, etc. Multi-field coupled numerical simulation for cure process of composites with time-dependent properties of materials. J. Acta Materiae Compositae Sinica. 2015; 32(1): 167-175.

[9] Wang X X, Jia Y X, Dong S H. Global sensitivity analysis of cure uniformity of fiber composite structures based on Morris method. J. Acta Materiae Compositae Sinica. 2015; 32(4): 1211-1217.

[10] He J L, Wang T, Pan R Y, etc. Analysis of isothermal cure uniformity of resin matrix composites based on dimensional analysis method. J. Acta Materiae Compositae Sinica. 2016; 33(1): 71-76.

[11] Wang J M, Zheng Z Z, Chen R C, etc. Cure Degree Field and Temperature Field Uniformity Optimization During Cure Process of Resin Matrix Composites. J. Engineering Plastics Application. 2015; 43(4): 55-61.

[12] Alfred C. L, George S. S. Cure of Epoxy Matrix Composites. J. Journal of Composite Materials. 1983; 17: 135-169.

[13] Joshi S C, Lam Y C. integrated approach for modeling cure and crystallization kinetics of different polymers in 3D pultrusion simulation. J. Master. Process. Technol. 2006; 174: 178-182.

[14] Bogetti T A, Gillespie J W. Process-induced stress and deformation in thick-section thermoset composite laminates. J. Journal of Composite Materials. 1992; 26(5): 626-660.

[15] LIANG Qun, CHEN Shuhua, FENG Xiping, etc. Numerical study of temperature field evolution during composite case curing process. J. Journal of Solid Rocket Technology.2018;41(4):498-531.

IAC-19-C4,IP,35,x51103

Electric Propulsion's Rational Application Range on The Small Spacecrafts

Alexey A. Sidorov[a]*, Viktor A. Pererva[b]

[a] *Department of Construction and Design, Oles Honchar Dnipro National University, 72 Gagarina avenue, Dnipro, Ukraine 49000, Lxsdrv@ftf.gmail.com*

[b] *Department of Manufacturing Technology, Oles Honchar Dnipro National University, 72 Gagarina avenue, Dnipro, Ukraine 49000, Pererva.viktor@gmail.com*

* Corresponding Author

Abstract

The satellite's descent time into the atmosphere dense layers can be longer than the time of the proposed active existence for sufficiently large satellites orbits altitudes range. Continuous support for orbit parameters is most relevant in low Earth orbits. Flight Control's SETS department is developing various Hall effect thrusters (HET) that have good performance and can be used to solve these problems. The paper discusses the prospects for the use of engines to maintain the Earth remote sensing satellites orbit in low Earth orbits. Comparison of the application field of SETS HET and traditional chemical thrusters for similar tasks is carried out. The trajectory parameters were calculated by numerical solving the spacecraft's motion differential equations in the Earth gravitational field under the solar radiation influence in a rarefied Earth atmosphere. The control system was considered such that it changes the daily time the engine is turned on to maintain an orbit altitude. Such a scheme for modeling the operation of the control system makes it possible to take into account the change in disturbing factors that are not known in advance. A comparative analysis of chemical thrusters and HET was performed. The HET propulsion system mass is less than the chemical thruster system for altitudes less than 450 km due to a significant reduction in the mass of fuel. The masses of the compared systems are commensurate for orbit altitudes of the order of 500km. The HET propulsion system weight reduction will be more than 2 times when it is used instead of a chemical thruster at altitudes from 300 to 450km. The results obtained can be used both in the new spacecraft design and in the existing solutions modifications to obtain more efficient use of the satellite launch mass. The main result of this study should be to ensure the most efficient use of the satellite starting mass. The considered methods of calculation can be useful in obtaining the necessary characteristics of newly created thrusters designed to solve similar problems.

Keywords: low orbits, electrojet propulsion, monocomponent propulsion, maintaining orbit

Acronyms/Abbreviations
HET – Hall effect thruster
sfu – solar flux unit

1. Introduction

The development of space technology requires new solutions, new ideas and constant improvements. There is a steady tendency to miniaturization of satellites in recent times. The number of annually launched satellites up to 500kg increased more than 6 times in the period from 2010 to 2018. The same trend continues in 2019. Trends indicate an increase in the number of small satellites launches. At the same time, the share of micro- and nano-satellites increased significantly. Such progress is largely due to the success in miniaturization of electronics and the space market commercialization.

The task of distributing satellites into orbits appears in the case of launching several satellites by one launch vehicle when the satellites orbits will be distinguished by altitudes and (or) inclination. The use of HET for this purpose will reduce the needed fuel amount compared with chemical propulsion systems. A similar deployment scheme is planned to be implemented by D-Orbit at the end of 2019 [1].

The tasks of satellite positioning and maintaining orbit parameters are crucial for a wide spacecraft's range. The most sensitive to the accuracy of positioning in space are navigation satellites and remote sensing satellites. There can be various perturbations of the orbit from the effects of the atmosphere on the satellite depending on the orbit altitude and solar activity.

Calculations [2] show that there is an increase in the time of descent by 2 times from 450km to 350km with a decrease in solar activity from 250sfu to 125sfu. The calculation was carried out under solar activity and atmospheric parameters constancy conditions. The parameters of the atmosphere can vary quite strongly even during one day of flight n real space flight conditions. Minor fluctuations will not have a big impact on the overall result.

For the average level of environmental parameters, it will be estimated to pass the same time as for real conditions.

It is important to choose the right type of thruster for the satellite at the development stage since many parameters will depend on the propulsion system. These parameters include the starting mass and dimensions of the satellite, power consumption, background radiation, operating temperatures and other.

Reducing the orbit altitude while remaining unchanged other characteristics will reduce the lifetime of the satellite or require an increase in the total pulse of the propulsion system to maintain the orbit. It should also be noted that some satellites need a certain spatial position to solve the tasks assigned to the satellites. It may be unacceptable to reduce the orbit altitude, even for a long time, and the parameters of the orbit need to be maintained.

For further consideration and comparison, a mono-fuel engine has been adopted (BGT-X5 characteristics [3]) and the best in terms of thrust to power ratio among electrojet [4] HET ST25 SETS [5] (Fig. 1)

2. Material and methods

Differential equations of perturbed motion in the presence of small perturbing forces can be written with respect to orbits osculating elements [6]. The object movement in the Earth gravitational field can be described using models of the gravitational field with varying degrees of accuracy [7]. The model of the central gravitational field for preliminary calculations was chosen. In accordance with the work [7], we take the big semi-axis of the Earth ellipsoid equal to 6378 km, and the small semi-axis - 6356 km. Mutual consideration of the difference in altitude and the diurnal change in the atmosphere density (especially the upper layers) shows the ratio of maximum to minimum atmospheric density up to seven [8].

The equations of motion are considered in the orbit plane. The spacecraft's trajectory parameters are obtained by differential equations of motion numerical integration with the Euler method. Test calculations were performed for several previously launched satellites for which the launch orbits are known at the time of the calculation. The numerical solution results of the equations and the spacecraft position on the orbit coincided with an accuracy of up to 5%. The error in the calculation results is caused by the use of an approximate model with average magnitudes as initial solar activity magnitudes. When the atmospheric calculation module is disabled, the equations are solved with an error of less than 0.01% (in comparison with the analytical calculation method given in [9, 10])

A spacecraft motion close to a circular orbit was chosen for analysis. Atmospheric parameters were taken for the equatorial spacecraft motion plane. The orbit eccentricity turned out to be of the order of 10–6 to 10–7 for all calculations.

The orbit correction during the day is performed by switching on the HET for various time. The HET operation time per day increases with decreasing flight altitude and vice versa. This orbit altitude support system behavior was taken on the basis of the solar activity magnitudes and the atmosphere parameters accurate prediction uncertainty at each time point. Insignificant deviations of the flight altitude from the one required for such a control scheme are obtained.

3. Theory and calculation

Specific models of electrojet and chemical thrusters were used in solving the set tasks. As an electrojet was taken a perspective HET ST25 manufactured by SETS. The monocomponent fuel thruster BGT-X5 on AF-M315E is taken as a chemical thruster.

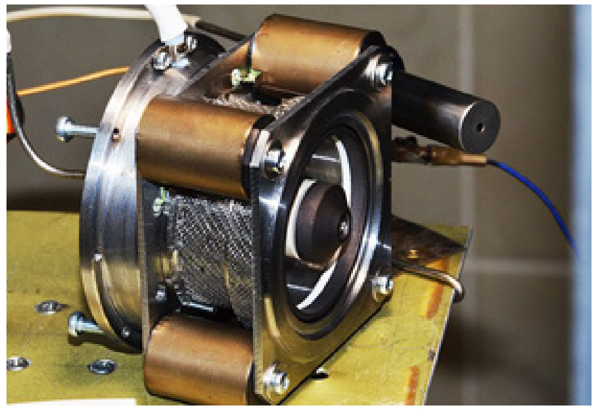


Fig. 1. HET ST25 manufactured by SETS

The values of HET total pulse are not available for the chemical thruster. The mass of the chemical thruster is significantly less than HET. A chemical thruster may be the most appropriate solution for small satellites that do not require large total pulses. Large thrust per unit mass of the chemical thruster allows to quickly change the parameters of the trajectory of the spacecraft.

The spacecraft motion in a circular orbit was analyzed with the orbit parameters being maintained separately by each of the engines under consideration. Calculations show that the amount of fuel required to maintain the orbit by the HET is more than four times less than that by the monocomponent one. From the criterion of the minimum mass, it may seem that in all cases the using of the HET is preferable. Consideration should be given to the smaller mass of the mono-component propulsion system and the absence of overall and heavy supplementary systems that exist in HET. The maintenance of a satellite's orbit with a mass of 250kg and the spacecraft's cross section area of $2m^2$, orbiting an altitude of 550km, was considered over five years period. The xenon mass required for the operation of the ST25 engine will be about 1.1kg. A similar task with using a monocomponent propulsion system will require 5.6kg of fuel. The application of the HET system will not give a positive effect if the mass of the structure and additional systems (cathode [11], feed system, power processing unit) of the HET is more than the chemical one by 4.5kg. The difference in the fuel mass will be 16kg for an orbit with an altitude of 450km in solving the same problem. The difference in the required amount of fuel will be about 8kg per year to maintain the parameters of the orbit with an altitude of 200km. The declared mass of the propulsion system ST25 is 6 kg. This makes it possible to determine the ranges of orbits, to maintain the parameters of which, it is preferable to use this HET.

Reducing the required circular orbit altitude gives an increase in the efficiency of the use of the HET as compared with the chemical one. Analysis of the results indicates that it is possible in principle to use ST25 to maintain the low orbit parameters. The lower limit of electrojet thruster's applicability is associated with a low pitch. For altitudes below 300km, in order to maintain the parameters of circular orbits, it will be necessary to turn on the HET for more than 50% of the time spent in orbit at a solar activity level of 125sfu. Consequently, half the time solar panels energy must be consumed to operate the thrusters but not the target equipment. Also, should be noticed that the fuel consumption to maintain the orbit parameters will be commensurate with the resource of the engine, which does not provide a reserve in case of emergency situations and the uncertainty of the initial parameters.

Based on the foregoing, it is possible to make a preliminary conclusion that the greatest effect from the use of an electric propulsion system based on HET ST25, based on the criterion of minimum mass, will be achieved for orbit altitudes from 300 km to 450 km.

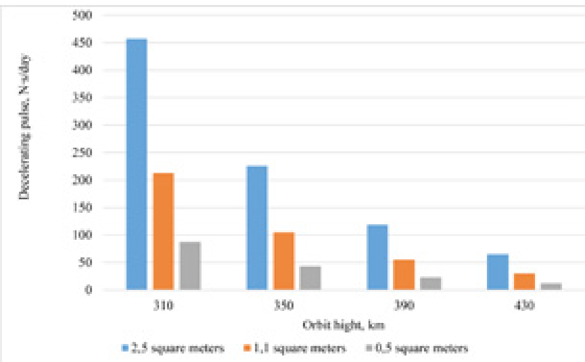


Fig. 2. Daily decelerating pulse of aerodynamic forces

To clarify the propulsion system characteristics, a decelerating pulse was calculated, which creates the aerodynamic drag force acting on a spacecraft in a circular near-Earth orbit at given levels of solar activity. The calculation was carried out according to the method described in [10]. Geometric parameters were assumed typical for this type of satellites. The decelerating pulse calculations result at the level of solar activity F = 200sfu for the various spacecraft's cross section area combinations are presented in Fig. 2.

The calculations result of the average daily HET operating time to maintain the spacecraft orbit parameters with the spacecraft's cross section area of 1.1 square meters, depending on altitude and solar activity, are presented in Fig. 3. Based on the characteristics of the propulsion system, the annual fuel consumption (Fig. 4) and the necessary resource of HET operation time (Fig. 5) for performing the considered tasks were obtained.

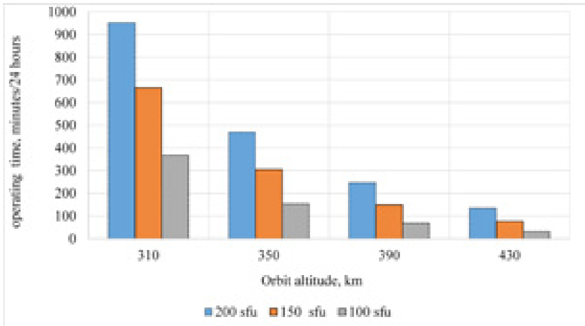


Fig. 3. Average daily operating time of the HET to maintain orbital parameters

The calculation of the required fuel amount was carried out on the basis of the equality of the decelerating pulse and the engine thrust pulse. The required resource is linearly related to the amount of fuel and is necessary to assess the possibilities for the implementation of a force pulse by the propulsion system.

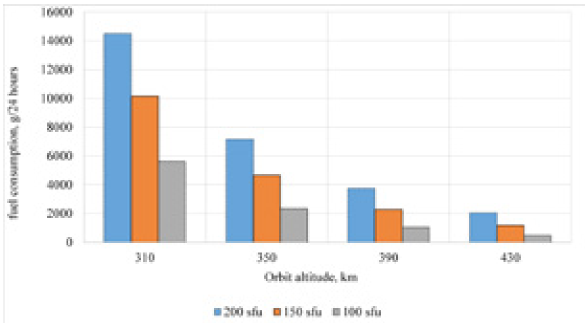


Fig. 4. Fuel consumption to maintain orbital parameters for the spacecraft's cross section area of 2.55 m²

The calculations results show that with solar activity close to the maximum HET operating time does not exceed 50% of the entire flight time. The total HET operating time is only a small fraction of the orbit time for the remaining variants. Considering the use of a spacecraft for the Earth remote sensing, it can be assumed that the engine can be switched on to maintain orbit over areas that are not being surveyed (for example, over the oceans). According to the results of the calculations, it is possible to make a conclusion about the effectiveness of the use of engines for the selected altitude range. The consumption of chemical fuel for such a task will be about five times higher than the HET fuel consumption.

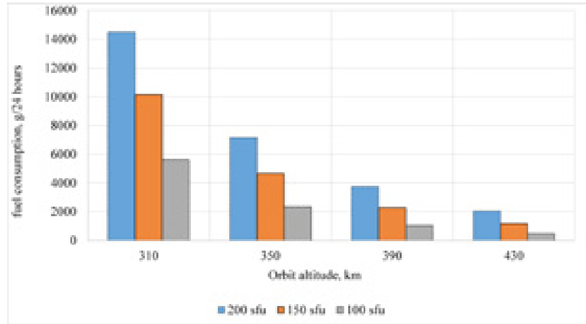


Fig. 5. The resource of HET operation required to maintain the orbit

The propulsion system mass is considered to consist of the engine, fuel and associated systems (for example, the flow control system). The mass efficiency of the use of propulsion systems various types is estimated by the total mass of the systems included in its composition.

For a propulsion system using the ST25 HET, the advantage in fuel reserves fully and with a large margin covers a total mass of the associated systems. This indicates a greater efficiency of the propulsion system based on the ST25 by the mass criterion in comparison with the monocomponent chemical propulsion system.

4. Results

The system with an electric propulsion system based on the ST25 will be expected to be used on spacecraft with a service life of more than a year. The calculation of the required fuel and engine life for 5 years of work in orbit in a given altitude range has been carried out. The calculation was carried out in accordance with the mathematical model of the spacecraft motion described above. The total time the HET was turned on was chosen so as to keep the spacecraft at a given altitude. Solar activity and the corresponding parameters of the atmosphere are predicted to launch a satellite at the end of 2020. The corresponding calculation results are given in Table. 1.

Orbit altitude, km	Fuel consumption, kg			Operation resource, thousands of hours		
	cross section area, m²					
	2,55	1,19	0,5	2,55	1,19	0,49
310	54.9	25.6	10.5	22.7	10.6	4.4
350	26.0	12.1	5.0	10.8	5.0	2.1
390	13.1	6.1	2.5	5.4	2.5	1.0
430	7.0	3.2	1.3	2.9	1.3	0.6

Table 1. The required resource of engine operation and fuel consumption to maintain orbital parameters over 5 years

From the Table 1 it can be seen that for the most altitudes combinations of the circular orbit and the spacecraft geometry in these orbits, the resource of one ST25 engine will be sufficient to complete the task. A system containing two identical HET can be used in the case of the planned excess of the resource of the one HET. The use of such a dual thruster system will make it possible to extend the service life to the required value and, if necessary, increase the thrust of the propulsion system to perform a quicker maneuver.

It follows from the results of the calculations that the use of low thrust HET is justified on small spacecraft with a power deficiency. If the spacecraft's cross section area is significantly larger than 2m2 then should be used more powerful HET, like ST40 [12].

5. Discussion

The results obtained are well compared with the results obtained in [9, 13, 14]. Other approaches to estimating the mass and dynamic characteristics of spacecraft used in these studies are mainly based on analytical methods for assessing the influence of various external factors on orbit parameters. In these articles were laid more accurate aerodynamic coefficients of specific satellites. The differences are up to 5%, which is negligible in the preliminary assessment.

6. Conclusions

The use of electrojet engines, such as the ST25 SETS, to maintain satellite orbit parameters may be useful for certain orbit ranges. The greatest efficiency (by mass criterion) of the use of electrojet thrusters will be to maintain the small satellites orbits with altitudes from 300 to 450km. In this case, it will be possible to reduce the propulsion system mass up to 40 kg when replacing the monocomponent chemical propulsion with the HET.

Acknowledgments

The team of authors thanks to the Space Electric Propulsion Systems department and personally the first deputy director of the company Viktor Serbin for assistance in conducting the study.

References

[1] J. Foust, D-Orbit to launch 10 Astronaut satellites on Vega rocket. August 7, 2018, https://spacenews.com/d-orbit-to-launch-10-astrocast-satellites-on-vega-rocket/, (accessed 10.06.19)
[2] V.V. Salmin, V.V. Volotsuev, S.V. Shihanov, Podderzhanie zadannyih orbitalnyih parametrov kosmicheskogo apparata s pomoschyu dvigateley maloy tyagi. Vestnik samarskogo gosudarstvennogo aerokosmicheskogo universiteta, #4(43) (2013) 248-254.
[3] BGT-X5 Green Monopropellant Thruster, http://www.busek.com/index_htm_files/70008517E.pdf, (accessed 10.03.19)
[4] D. Krejci, P. Lozano, Space Propulsion Technology for

Small Spacecraft. Proceedings of the IEEE, vol. 106, no. 3 (2018) 362–378.
[5] SPS25 propulsion system, https://sets.space/sps25/, (accessed 10.03.19)
[6] A.P. Alpatov, Dinamika kosmichesih letatelnyih apparatov, Naukova dumka, Kiev, 2016.
[7] O. Montenbruck, E. Gill, Satellite orbits. Models, Methods, Applications. Springer, Berlin, 2015
[8] A.I. Maslova, A.V. Pirozhenko, Izmeneniya plotnosti atmosferyi pri dvizhenii kosmicheskih apparatov na nizkih okolozemnyih orbitah. KosmIchna nauka I tehnologIya, #1. (2009) 13-18.
[9] S.A. Ishkov, Analiz effektivnosti primeneniya elektroreaktivnyih dvigateley dlya zadach podderzhaniya okolokrugovyih orbit. Vestnik Samarskogo gosudarstvennogo aerokosmicheskogo universiteta, vol. 15, no. 1 (2016) 55-63.
[10] H. D. Curtis, Orbital Mechanics for Engineering Students (3rd ed.). Butterworth-Heinemann, 2013
[11] V. A. Pererva, E. V. Karpovich, A. V. Fedosov, Development of penetration zone size prediction technique for hollow-cathode welding technology of spherical titanium tanks. Eastern-European Journal of Enterprise Technologies. 2016. Vol. 1, Issue 5 (79). P. 47–52. doi: https://doi.org/10.15587/1729-4061.2016.59790
[12] ST40 - Electric Propulsion SETS, https://sets.space/st40/, (accessed 20.05.19)
[13] S.A. Ishkov, Optimization of Design Parameters of Spacecraft Equipped with Electro Rocket Low-thrust Engine and Calculation its Applying Area at Low Earth Orbit. Procedia Engineering, Volume 185 (2017) 239-245.
[14] A. Sidorov, V. Pererva, Determining the regions for efficient use of electrojet lowthrust engines. Eastern-European Journal of Enterprise Technologies. 2019. Vol. 3, Issue 5 (99). P. 47–52. doi: https://doi.org/10.15587/1729-4061.2016.59790

IIAC-19-D3.IP.3,x50245

Incorporating Sustainability into Planned Lunar Missions: Building Blocks for Lunar Settlement through Lunar Sustainability Goals

Scott Ritter,* Cody Bauer, Julie Bausmayer, Orr Cohen, Abhishek Diggewadi, Katie Harris, Aurelio Kaluthantrige, Monika Lipinska, Chenglan Liu, Linquan Mao, Pablo Melendres Claros, Charlotte Nassey, Lotte van Noetsele, Farnoosh Sheini Dashtgol, Andrew Townsend, Salvatore Vivenzio, Jeremy Wain Hirschberg, Xing Xu, Fabio Zecca, Ana Cristina Baltazar Garduño, Danijela Ignjatovic Stupar, Volker Damann

International Space University, 1 Rue Jean-Dominique Cassini, 67400 Illkirch-Graffenstaden, France
* Corresponding Author, scott.ritter@community.isunet.edu

Abstract

Future lunar surface and gateway missions are being proposed and supported by a range of actors, namely commercial companies, national space agencies, academics, and non-governmental organizations. In many instances, these actors have published their own mission strategies and phases for developing a lunar settlement. While these plans differ in their timelines and end objectives, they share a building blocks approach that transitions from robotic investigation, to establishment of infrastructure and habitats, arrival of humans, long-term missions, and eventually an established human settlement. Although the literature provides broad evaluation of the technical, scientific, and international requirements for achieving these plans, it contains significant gaps in evaluating the sustainability of these proposals. These issues are important because future lunar activity will likely rely on international, cooperative, sustainable strategies, rather than past unilateral, geopolitically driven, short-term strategies. To address these insufficiencies, this paper reviews a variety of roadmaps and establishes a consolidated five-phase summary of these roadmaps, with details for the infrastructure, human factors, political, and economic prerequisites, to outline the gaps in sustainability evaluation. These gaps are then organized into Lunar Sustainability Goals, which can be integrated into planned lunar surface missions. These fifteen goals, developed in line with the United Nations Sustainable Development Goals (SDGs), the Committee on the Peaceful Uses of Outer Space (COPUOS) Long Term Sustainability of Outer Space Guidelines, and in consultation with the broader space community, are: (1) Open Access, (2) Peaceful Purposes, (3) Diversity and Opportunity, (4) International Cooperation, (5) Education and Outreach, (6) Environmental Protection, (7) Heritage Protection, (8) Health and Safety, (9) Sustainable Transportation, (10) Standardization, (11) Space Debris Prevention, (12) Zero Waste, (13) Sustainable Energy, (14) Sustainable In Situ Resource Utilization, and (15) Earth Applications. Ultimately, these goals, along with their accompanying targets and drivers, help frame future mission plans in terms of an internationally cooperative, building blocks approach to lunar settlement.

Keywords: roadmaps for lunar settlement, lunar development, lunar sustainability goals

Abbreviations

COPUOS	Committee on the Peaceful Uses of Outer Space
CNSA	China National Space Administration
CSP	Concentrated Solar Power
ESA	European Space Agency
EVA	Extravehicular Activity
ISECG	International Space Exploration Coordination Group
ISRU	In Situ Resource Utilization
ISS	International Space Station
JAXA	Japanese Aerospace Exploration
Agency	
LSS	Life Support System
MELiSSA	Micro-Ecological Life Support System Alternative
NASA	National Aeronautics and Space Administration
RHU	Radioisotope Heater Units
RTG	Radioisotope Thermoelectric Generator
SDGs	Sustainable Development Goals
UNOOSA	United Nations Office for Outer Space Affairs

Introduction

Numerous commercial companies, national space agencies, and private organizations have independently developed lunar exploration roadmaps for returning to the Moon. While these roadmaps have different underlying rationales (discussed in IAC-19-D4.2.8 [1]), many share a basic phased approach moving from (1) robotic investigation, to (2) establishment of infrastructure and habitats, to (3) habitat development, to (4) long-term missions and permanent human habitation, to (5) establishment of a developed settlement and lunar society. A consolidated summary of these general phases is shown in Figure 1 and further described herein.

The various lunar exploration actors and their approaches to lunar settlement are presented in Table 1 below. These actors have varying approaches and timelines for their proposed lunar activities. For instance, all entities outlined in Table 1, except SpaceX and Blue Origin, include aspects of prospecting lunar resources before further development on the surface. Others such as ispace, NASA, and the National Space Society begin habitat development after confirmation of resources.

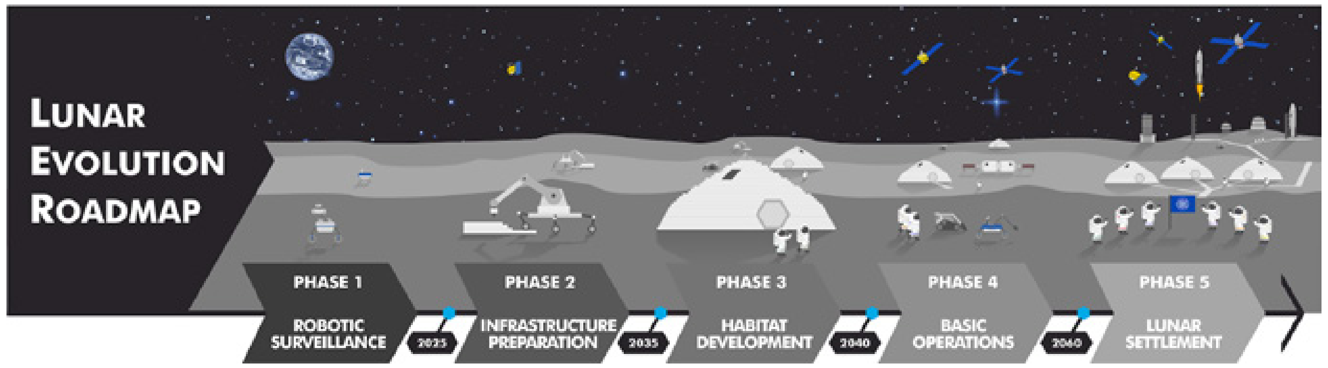


Figure 1. General phase approach to lunar evolution

One key aspect missing from the roadmaps presented above is substantial consideration of sustainability. Through our consolidation of existing lunar settlement roadmaps, we highlighted areas in which we believe a focus on sustainability is important. This led us to define 15 Lunar Sustainability Goals, which are described below. The second section of this paper will describe our consolidated five-phase roadmap, which is intended to be carried out under the guidance of these 15 goals.

Phases	Companies						Space Agencies						Orgs.		
	Moon Express	Airbus	ispace	Lockheed Martin	Blue Origin	SpaceX	ESA	JAXA	NASA	KARI	Roscosmos	CNSA	Global Exploration Roadmap	National Space Society	International Space University
1	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓
2		✓			✓	✓	✓	✓		✓	✓	✓	✓		✓
3		✓	✓	✓	✓	✓	✓		✓		✓	✓	✓	✓	✓
4		✓	✓			✓	✓		✓					✓	✓
5			✓			✓								✓	✓

Table 1. Companies, space agencies, and organizations with lunar evolution roadmaps [2-17]

Lunar Sustainability Goals

Our approach to sustainability follows in the footsteps of the United Nations Brundtland Commission that defined sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" [18]. This definition inspires the following Lunar Sustainability Goals and extends practices currently employed on Earth.

The following Lunar Sustainability Goals serve as guidelines that all lunar and cislunar space actors should consider. Inspired by the United Nations SDGs on Earth, these goals aim to address sustainability challenges before they become critical and promote sustainable activities on the Moon.

Goal 1: Open Access. Aims to ensure access to the Moon and cislunar space is open to all states, actors, and activities. This ensures fair access to the lunar surface and resources, encourages international cooperation, and promotes compliance with international law for all lunar activities.

Goal 2: Peaceful Purposes. Aims to ensure that the Moon and cislunar space are dedicated to peaceful purposes. Peaceful use of the Moon is a vital prerequisite for many of the other Lunar Sustainability Goals, such as Open Access and International Cooperation, and will also set a precedent for peaceful relations between states regarding Earth.

Goal 3: Diversity and Opportunity. Aims to encourage all lunar actors to commit to achieving diversity within their workforces to include the perspectives and expertise of various groups, making the Moon the province of all humankind. Goal 3 considers diversity as aiming for a balanced representation of men, women, and under-represented groups within the workforce.

Goal 4: International Cooperation. Aims to foster international cooperation through partnerships and collaboration between diverse actors. This is accomplished by bringing nations together to cooperate on sustainable lunar developments.

Goal 5: Education and Outreach. Aims to raise awareness of the importance of a sustainable approach for Moon activities and programs. This is done through promoting education and outreach for environmentally and socially responsible future lunar missions.

Goal 6: Environmental Protection. Aims to ensure the preservation of the lunar environment. This is done by applying the concept of environmental protection to the Moon, to preserve the natural lunar environment and to avoid unnecessary changes or thoughtless pollution.

Goal 7: Heritage Protection. Aims to ensure the preservation of heritage sites on the Moon. This is done by preserving the natural, cultural, and scientific heritage of the Moon.

Goal 8: Health and Safety. Aims to ensure that missions to the Moon are undertaken with the highest levels of safety and that sufficient astronaut rescue and emergency protocols are in place. To achieve a sustainable lunar settlement, human health and safety should be at the forefront of mission planning to increase the probability of an overall state of wellbeing for those involved in travelling to, and living on the Moon.

Goal 9: Sustainable Transportation. Aims to encourage the development of innovative sustainable infrastructure for transportation to the Moon and in cislunar space. This goal is important to ensure future transportation will support traffic control regulations and consider the sustainable use of lunar resources.

Goal 10: Standardization. Aims to ensure the development of international standards as a key instrument for the application of the Lunar Sustainability Goals. There are two aspects to consider for standardization: (1) the identification of applicable technology, and (2) the scope of participants in the standardization process. It is necessary to promote cooperation between various space and non-space actors to adopt consolidated standards, and ensure sustainable development of systems on the Moon. Standardization is also a key instrument for long-term international collaboration while ensuring Open Access (Goal 1).

Goal 11: Space Debris Mitigation. Aims to prevent the accumulation of debris in the Earth-Moon system to ensure safe and sustainable lunar missions. This is done by removal of space debris from Earth orbits, and preventing the occurrence of similar pollution in lunar orbits to ensure safe and sustainable missions.

Goal 12: Zero Waste. Aims to prevent the production and disposal of waste on the lunar surface. This is done to achieve sustainable habitation on the Moon for future long-term lunar crewed missions, which will require significant amounts of food, water, and propellant supplies. Carrying these supplies from Earth or relying on resupply missions is impractical, which makes closed-loop systems a necessity for long-term lunar exploration missions.

Goal 13: Sustainable Energy. Aims to ensure the sustainable generation, storage, and distribution of energy. Goal 13 is at the basis of all lunar activities because sustainable energy use is a determining factor for long-term presence on the Moon. The energy produced and stored should be safely and efficiently distributed to make the most of its limited availability.

Goal 14: Sustainable In Situ Resource Utilization. Aims to ensure low environmental impact of activities that require the use of lunar resources. Goal 14 focuses on the limited nature of lunar resources, such as minerals and regolith, but also frequencies, and orbitosphere. Additionally, ensuring the sustainability of a long-term lunar habitation entails operating mostly with in situ resource utilization (ISRU).

Goal 15: Earth Applications. Aims to ensure that activities on the Moon improve life on Earth through scientific advancements and spin-offs. Many of the proposed activities to be carried out on the Moon could benefit Earth directly, and these should be prioritized until the lunar activity can generate its own revenue and become self-sustaining. These activities include the economic benefits created by multipliers, spin-offs, and spin-ins described in IAC-19-D4.2.8 [1], all of which could assist activity on Earth and should therefore be prioritized to ensure a sustainable level of interest and investment amongst relevant stakeholders.

These goals should inform the planning processes undertaken by various lunar actors as they progress through the generic phases of lunar settlement described below.

Phase 1: Robotic Surveillance (Present - 2025)

In most of the roadmaps listed in Table 1, an initial "Robotic Surveillance" phase assesses the lunar environment, establishes resource abundance, and determines potential habitat sites. Uncrewed spacecraft carry out investigatory missions to determine the suitability of potential locations for a lunar settlement (Table 2), characterize the resources available, where they are most abundant, and what their abundance is. This phase typically supports the scientific and technological rationales for lunar exploration discussed in IAC-19-D4.2.8 [1]. The need to identify which resources are located where and in what quantity are also the basis for developing a future lunar economy, also discussed in IAC-19-D4.2.8 [1].

Phase 1 Infrastructure

Power and Distribution. Only limited power is needed in Phase 1, since low power demand surveillance activities will predominante. Sustainability is essential for the power and distribution system, since current international treaties require avoiding polluting the Moon [19]. However, existing roadmaps failed to consider the sustainability of their power infrastructure, which led to the creation of Goal 13: Sustainable Energy. The potential power sources could be a combination of photovoltaic arrays and batteries for storage as part of rover designs, which would allow for scaling in future phases, in line with sustainable settlement.

Alternatively, radioisotope heater units (RHU) or radioisotope thermoelectric generator (RTG) could be implemented, which have flight heritage and little sensitivity to temperature gradients and radiation. However, due to the radioactive decay process, methods of radioactive disposal must be addressed to ensure the sustainable exploration of the Moon while generating zero waste (Goal 12: Zero Waste).

Communication. Some missions may not need developed communications architecture, as they would use direct communication with ground stations on Earth using radio frequencies which were also used for the Apollo missions [20]. Any robotic mission conducted past the horizon, in a crater, or out of its lander or orbiter's line of sight will require an orbital relay satellite.

Lunar Site	Key Features
South Pole (rim of Shackleton)	· Near-permanent sunlight for power production · Oldest Lunar impact feature for science missions · Cold trap present (may contain water ice)
North Pole (rim of Peary B)	· Near-permanent sunlight for power production · Cold trap present (may contain water ice)
Rima Bode	· Extensive high-Ti mantle deposits (useful for ISRU) · Exotic Xenolith ash deposits for science missions · Based in equatorial region (easy access)
Aristarchus Plateau	· Diverse geological area for science missions · Contains pyroclastic deposits (useful for ISRU)
Orientale Basin Floor	· Unique crater morphology for science missions · Contains mare & highland regolith (useful for ISRU)
Central Far Side Highlands	· Primordial crust for science missions · Al- and Ca-rich regolith (useful for ISRU) · Low-frequency radio sky for astronomy missions

Table 2. Current high priority lunar outpost sites [25]

Navigation. To permit rover surface exploration and operation in areas far from the landing site, a ground-based lunar navigation system using machine-vision-based autonomous navigation mapped to satellite generated ground images could be employed [21].

Transportation. Scientific lunar surface surveillance missions would require instruments to be transported from Earth. Standard chemical propulsion transport, at estimated per kg cost of $35-70,000 USD, is planned [22]. To reduce these costs, programs such as the Commercial Lunar Payload Services have been established, which allow selected companies (e.g., Lockheed-Martin, Moon Express, Orbit Beyond) to deliver scientific payloads to the Moon at reduced cost [23]. Given the nature of these prospecting missions, the need for transport back to Earth is not required. However, for surface-based surveillance missions via rovers, soft landings are required, which has thus far only been achieved by the US, Russia, and China [24].

In Situ Resources. A major lunar resource of interest is water ice, which could eventually be useful for astronaut life support and fuel production through electrolysis. Past missions have identified its presence in the polar regions, deep within permanently shadowed craters, and even trapped within the lunar regolith itself [15]. Basaltic lava regions also have compositions of metals (i.e., iron, titanium, aluminum) and silicon, which could be useful for habitat construction and mirror fabrication [26].

Phase 1 Governance

In initial phases, international governance is planned to sustainably coordinate the activities of countries with planned missions for robotic exploration of the lunar surface (i.e., China, South Korea, Russia, India, Israel, Japan, US, and the European Space Agency (ESA) member states). As it exists today, governance mainly consist of international partnerships and agreements (e.g., the International Space Station (ISS) and the International Space Exploration Coordination Group (ISECG)), which could be extended to the Moon and should expand to incorporate new members (Goal 4: International Cooperation). Guaranteeing open access (Goal 1) to the Moon for new actors forms the basis of initial governance, from which other more complex governance could develop over time as the phases develop. Safety zones (operational boundaries) are also established to ensure the non-interference of lunar surface operations (Goal 2: Peaceful Purposes). Well implemented governance will enable sharing of crucial ongoing and future lunar activity information, including mission objectives, area of operation, and mission duration, and will create an environment for collaboration and the sharing of scientific data.

Phase 1 Summary

Collectively, robotic surveillance phases focus on assessing in situ lunar resource usability via in-orbit remote sensing and rovers. Potential outpost locations are identified

AD ASTRA – IAC Special Issue – 2019

by considering local terrain, energy availability, and communications. Power requirements are mission-specific and achieved with on-board equipment, such as solar arrays and RTGs, if proper waste disposal is available. Communications during this phase are based on line-of-sight to Earth ground stations or relay satellites, with navigation using autonomous machine-vision of ground images. Equipment transportation would be reliant upon chemical propulsion and can use Commercial Lunar Payload Services. To achieve these tasks, international partnerships between lunar actors and international governance are needed.

Phase 2: Infrastructure Preparation (2025 - 2035)

In most roadmaps, a second "infrastructure preparation" phase establishes the systems necessary for long-term crewed lunar surface missions, with durations averaging about 10 years. Initially, lunar infrastructure is installed by robots. This initial infrastructure will provide structural support, radiation and micrometeor protection, and dust exposure reduction, to address human health concerns for lunar settlement, discussed in IAC-19-D4.2.8 [1]. Roadmaps from Airbus, ESA, and the Global Exploration Roadmap (ISECG), describe the time and resource investment required for infrastructure preparation. However, no roadmaps establish the goal of determining the volume of useful resources (e.g., water) that could be mined to ensure resource and economic sustainably (Goal 14).

Phase 2 Infrastructure

Infrastructure preparation is influenced largely by resource availability at a selected site, which is determined during Phase 1, above. However, multiple infrastructure preparation concepts exist, and are described below.

Architecture. Rigid structures with thermal protection systems have been suggested for robots to prevent damage to components caused by exposure to the lunar environment [27]. To reduce costs associated with transporting these structures from Earth, ISRU has been suggested as a first infrastructure preparation step, for example, through regolith 3D printing, solar sintering, or ice implementation [28-30].

Power and Distribution. Here, infrastructure to power robot operations, including energy generation, storage, and distribution, is planned for development and reliability testing. ISRU for these systems would decrease Earth resource dependence, but should be conducted sustainably (Goal 14: Sustainable ISRU) to allow other space actors to utilize similar resources (Goal 1: Open Access, Goal 4: International Cooperation). RHUs and RTGs in Phase 1 would not provide sufficient energy, so easy-to-install and maintain solar arrays would be ideal, particularly for polar sites [15]. However, if solar arrays would not suffice, compact nuclear fission reactors could meet these needs (e.g., NASA's KiloPower (10 kWh over 10 years) [31]; and ESA's Lunar Surface Reactor (100 kWh over 10 years) [32], and serve as a backup source in case of other system failures, to support Goal 8: Health and Safety. Furthermore, implementing a standardized method of power transfer during this phase would be beneficial, and support Goal 10: Standardization. It would allow instant access to power, regardless of the circuitry within the lunar equipment, robots, or future human settlement components while also promoting the involvement of international partners (Goal 4: International Cooperation) due to the standardized power system. This would also benefit habitat preparation, where no significant power infrastructure has been developed, yet.

Communication. Communication between orbiters, autonomous robots, and rovers on the lunar surface is planned for line-of-sight and non-line-of-sight alternatives [33]. Should radio signal delay of greater than five seconds occur, it is recommended that robots use automated subroutines to ensure safety and efficiency to avoid time delay problems associated with human-in-the-loop telerobotic commanding and monitoring [34].

Navigation. To provide the precise ground navigation required for remote robotic construction, a celestial based navigation system could be developed with star trackers and sun sensors, making it independent of ground facilities [35-36].

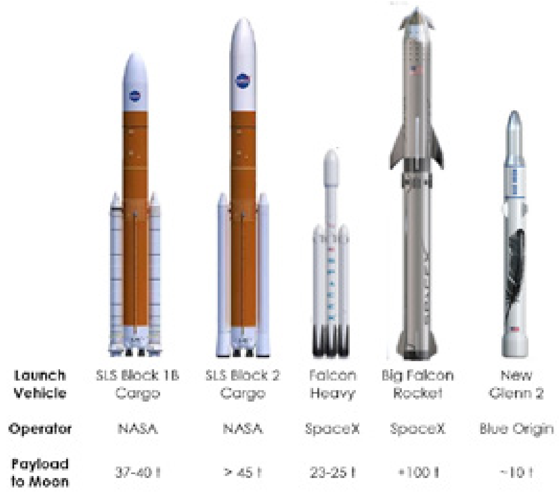


Figure 2. Comparison of heavy launch vehicle capabilities [37]

Transportation. As shown in Figure 2 below, a combination of national agencies and commercial companies are developing the ability to launch 50 metric ton payloads to the Moon [37]. Commercial companies (e.g., SpaceX and Blue Origin) have developed reusable launch vehicles to reduce production costs (Goal 9: Sustainable Transportation), and mitigate space debris (Goal 11). The ability to perform soft landings with high payload mass is critical to the success of the phase, so development of guidance systems that use landmark recognition to touch down softly could facilitate safe cargo delivery and avoid inadvertent landings in undesirable areas, such as heritage sites (Goal 7: Heritage Protection) [38].

In Situ Resources. Lunar regolith has been identified as a main resource for base structure development. Useable amounts of metals and composites would be implemented for construction, so the collection of in situ resources (e.g., lunar regolith) for constructing habitats would be the primary focus. This would involve small scale mining via on-site robotics, which would establish the foundation of resource collection that can later be scaled in future phases. Before using the raw materials, methods of chemically processing the regolith to extract useful resources is required. Fluorine has been identified as a possible catalyzer. This process involves heating the regolith in the presence of fluorine, which binds to silicon and titanium components within the regolith, while displacing oxygen [39]. The remaining by-products can be re-condensed, allowing extraction of the fluorine, making the process repeatable and sustainable per Goal 14: Sustainable ISRU.

Phase 2 Governance

This phase aims to establish the basis for the habitat. Here, the need for operational boundaries is important, but the extent of the governance required will depend upon the composition of the actors on the lunar surface (e.g., one country or several countries, public or private organizations). The current legal framework regarding the exploitation and appropriation of lunar resources for this phase is limited because while the Moon Agreement specifies that the Moon's resources are the common heritage of humankind (Article XI) and provides for governing its exploitation, the parties that ratified the Moon Agreement are too few to have an impact on tackling these issues [40].

Some scholars believe that resources separable from the ground of a celestial body would have a different legal status than the lunar ground itself, which could be a way of allowing ownership of extracted resources [41]. This approach would be a new challenge for outer space activities, and forming an international consensus would be essential for a lunar base with resource extraction activities [42].

United Nations Office for Outer Space Affairs (UNOOSA) and COPUOS can help define the best approaches for resource utilization. Soft-law can help guide activity outside and beyond international treaties, such as the Moon Agreement, and can incentivize space actors to adopt sustainable behaviors. However, it is important to note that many of these soft-laws are created in parallel with each other, creating duplication, and often at odds with one another, allowing for select picking of space nations to follow policies that best suit their aims and activities [43]. Therefore, having a consolidated set of policies that are agreed upon, similar to the United Nations SDGs for Earth, is necessary.

Phase 2 Summary

With outpost sites identified and resources characterized during Phase 1, robotic infrastructure preparation and technology demonstrations can begin. In situ manufacturing of rigid structures, 3D regolith printing, and autonomous robots can all aid in construction, as powered by photovoltaic solar arrays and compact fission reactors. Line-of-sight and surface communications can be deployed to handle robotic system command alongside automated subroutines. Reusable commercial launchers provide material and robot transportation from Earth to the Moon. To govern resource utilization, updated legal frameworks should be developed that support commonly agreed upon policies, similar to the United Nations SDGs. Completion of this phase would allow the first astronauts to be on the lunar surface for short durations, where continued base development would begin, as described in Phase 3.

Phase 3: Habitat Development (2035 - 2040)

Many roadmaps include a "habitat development" phase, which establishes humans on the lunar surface using a series of short duration crewed missions. These 1-2 week missions involve building upon the infrastructure developed robotically in Phase 2 so that the Moon is suitable for long duration crewed missions of 6-10 people. This would be achieved through cooperation between the new lunar crews conducting the missions and robots, which would already be present on the surface, along with new robotic technology that may be sent. Together, they can produce fully pressurized, completed habitats and a living environment, similar to the ISS, to lay the foundation for larger operations. This phase will be concluded when there is infrastructure in place to sustain a permanent human presence on the Moon, with crew members rotating approximately every six months per year [34].

Phase 3 Infrastructure

Phase 3 infrastructure plans address the expansion required for long-term operations, which includes additional habitat structures tailored for human occupation, their power, communications, and navigation systems, and expanded in situ resource collection.

Architecture. Here, the architectural goal would be a fully pressurized habitat, capable of the same level of operations as the ISS, the pressurized volume of which equates to 916 cubic meters, including 388 cubic meters of habitable volume [44]. Similar to the ISS, the number of crew would be determined by the evacuation capabilities, in line with Goal 8: Health and Safety. The pressurized modules can be transported from Earth to ensure increased reliability and Earth-based testing, over in situ production. Habitable modules can be either rigid, as are ISS modules, or deployable/expandable, like the Bigelow Expandable Activity Module. Using thin-membrane inflatable modules is easier to transport from Earth than rigid modules, but surviving harsh lunar conditions requires additional radiation and micrometeorite protection [45].

Power and Distribution. New robots, vehicles, habitats will increase energy demands rapidly. To meet this demand,

an alternative method for collecting solar energy may be implemented, such as Concentrated Solar Power (CSP), which uses mirrors to redirect sunlight to a solar energy collector [46], but requires precise alignment and human setup. Reusing parts of rockets, rocket stages, and tugs has been suggested as a sustainable approach to improve the power-to-weight ratio of CSP systems. As shown in Figure 3, components such as the nose cone, and rocket tank/stage could be pre-manufactured with reflective coatings, and later set up to concentrate solar energy from the Sun. Moreover, the second stage propulsion tanks could be reused as on-site storage tanks for in situ production of hydrogen, oxygen, and water [47].

Communications. The Phase 3 communication requirements are specific to the individual crewed missions that will be conducted. However, Phase 3 plays a vital role in preparing for the later phases including the development of more robust communication platforms for the operations that will take place during Phase 4.

Surface Communication. Here, communication links could be astronaut-to-astronaut, astronaut-to-robot/rover, between the lunar base and the Extravehicular Activity (EVA) crew, and facilities. For these purposes, the use of omni-directional Very High Frequency antennas system could provide the necessary capabilities for these communication requirements. Relay satellites could be used for point-to-point lunar communications when there is no line of sight [33].

Earth-Based Communications. Here, it is anticipated that the amount of scientific data transfer required for missions will increase. Schedules would need constant updating and live-feed video surveillance of the crew would be desirable for mission safety and public outreach (Goal 5: Education and Outreach). The increased amounts of data transfer would still be carried out by traditional RF communication systems, with the support of the relay satellite systems

Navigation. Navigation capabilities would need expansion for crewed missions and human exploration of the lunar surface. While the rudimentary positioning system used to coordinate robotic activity in Phases 1 and 2 could be relied upon as a basis, refining the localization capabilities of the system would be important for safety and efficiency of crewed missions.

Transportation. The arrival of humans to the Moon would require far more reliable systems of transportation, compared to those presented in earlier phases. Soft landings conducted in previous phases for cargo drops would be analogous to the method of transportation for humans to the lunar surface in this phase. However, safely landing humans on the Moon is a feat that was achieved nearly 50 years ago, and has yet to be replicated since.

Surface-to-Low Lunar Orbit Transport. While direct transfer to the lunar surface is feasible, it is possible that during Phase 3 there could be other technological developments for transference of humans to and from the lunar surface. Roadmaps produced by NASA and ESA have referenced the use of an in-orbit platform to facilitate the transportation of humans to and from the lunar surface. One example of this is NASA's Lunar Orbital Platform Gateway [50]. To test the reliability of the human landing systems and overall safety, a series of operational steps should occur, as outlined in Bridenstine and Gerstenmaier [51]. Overall, implementing a reusable system for human transport leads to lower costs, higher access frequency, and increased reliability of lunar surface transport, and directly supports Goal 9: Sustainable Transportation.

Three commercial launchers provide another lunar descent element and two refueling elements for the transfer vehicle and ascent element, respectively. The same three-element infrastructure used to deploy a four-person crew to the lunar surface in the same fashion as seen in Step 2.

Surface Transportation. Using the Apollo missions as an analog, the use of unpressurized Lunar Roving Vehicles allowed access to the surrounding terrain from the lunar module of up to 7.6 km during Apollo 17 in 1972. Similar

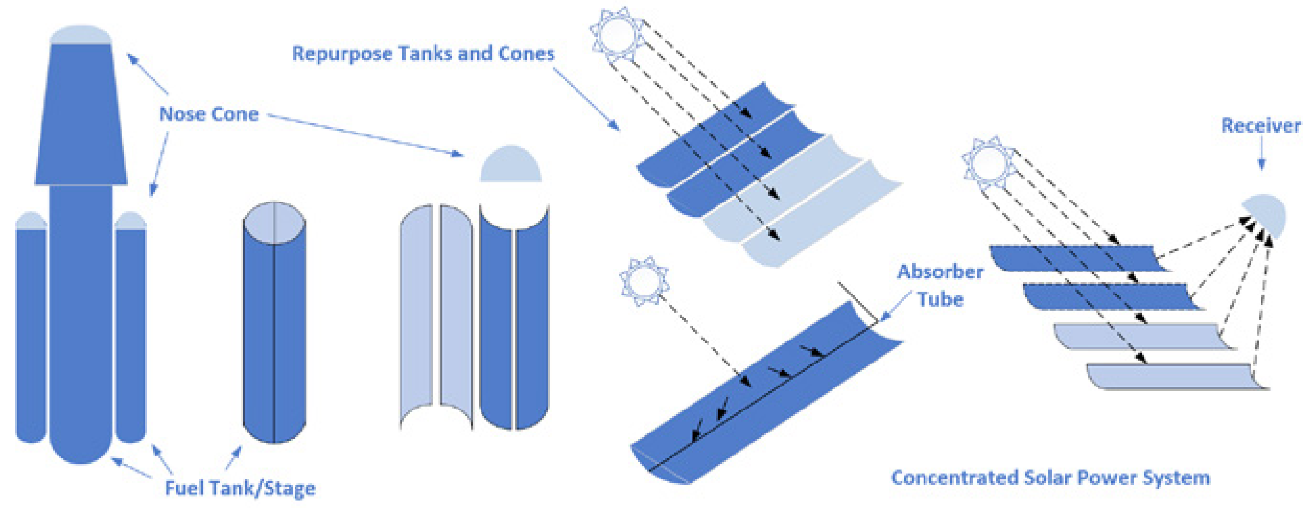


Figure 3. A CSP system constructed by reusing parts of fuel tanks and tugs

technology could be used for surface exploration involving lunar-geology missions or long distance mining operations. The Lunar Roving Vehicles developed during the Apollo era operated using an electrical power source (batteries). However, improvements in battery technology since 1972 could increase the maximum range to over 120 km [52].

In Situ Resources. This phase provides an opportunity to develop the larger infrastructure required for an in situ resource collection operation, in parallel with the development of the human habitation. While some in situ resources would be used up until this point, the majority of the past activities would consist of using regolith and other easily accessible surface resources. In this phase, the required machinery could be brought to the Moon to begin something similar to a small-scale mining operation, where below surface resources could be extracted and refined for other uses. The resources include water, semiconducting compounds and other heavy metals that have been referred to both in Phase 1 of this roadmap and in IAC-19-D4.2.8 [1]. This phase is only preparatory in terms of bringing the required equipment and developing the extraction site(s). All larger scale resource collection, refinement and utilization would take place as part of the operations of Phase 4

Phase 3 Governance

With Phase 3 signifying the first-time humans have returned to the Moon since 1972, the level of governance required expands beyond global governance on Earth, to local (operational) governance on the Moon. Operational governance is essential to ensure human health and safety, and create an environment that allows for the base to extend its capabilities.

The local governance required to maintain control over different emerging space activities with the arrival of the first wave of humans to the Moon could build upon existing international agreements such as the Antarctic Treaty, which uses a consensus-based approach to ensure appropriate uses and broad activities (e.g., science, tourism, maritime, etc.). The local governance is a form of public-private partnership which divides duties between stakeholders. [53-55].

Over time, as activities develop and areas such as lunar ISRU become operational, lunar governance may shift to represent something similar to the high seas. The United Nations Convention on the Law of the Sea could be a useful analog in that it serves to manage the ocean and protect its resources while allowing for commercial activities and resource extraction. For the Moon, information from all possible stakeholders regarding development plans would be needed to design an inclusive operational management system that provides benefits for all stakeholders [53-55].

Phase 3 Human Aspects

Herein are details regarding life support systems, medical capabilities, safety precautions, and organizational frameworks. Most of the life support and medical specifics within roadmaps describing this phase depend substantially on the specific requirements of the crewed missions to the Moon that will take place. However, it is essential that a foundation is established in all of these factors as early as possible, such that they are developed adequately and potentially support a growing, permanent human presence on the Moon.

Life Support. Although robotic missions would have already begun extracting lunar resources to produce water and oxygen for use in Life Support Systems (LSSs), this phase would rely on supplies carried from Earth. On the ISS, there is a partially closed-loop LSS that is able to recycle water and oxygen, but still heavily relies on resupply from Earth. Due to the distance circumstances, resupplying the Moon will be more complex and require higher costs than resupplying the ISS and therefore, establishing the basis of larger scale food production, hydroponics and other means of capturing and repurposing waste material will be essential to transitioning to later phases [56]. Outside of the lander modules, the crew would require EVA space suits.

Medical Capabilities. Due to the short duration of the crew's mission on the lunar surface, it is not necessary to have the complex medical capabilities that would be required by larger populations that would be on the Moon for longer durations in later phases. Missions would require medical accessory kits such as the one on the Apollo 11 Command Module [56].

Phase 3 Summary

Phase 3 represents the transition between exploration and habitation. At the beginning of the phase, the first crewed missions are sent to the Moon, to support the increase of production and construction capabilities of the robots that are already there. Together, the robots will work with a series of crews to construct infrastructure to sustain human life continuously (e.g., habitats, power sources, and communication, navigation, and transportation systems) and develop LSSs. At the end of the phase, the infrastructure is sufficient to house 6-10 people, for six months to a year. The milestones in this phase can be seen as analogous to those that occurred during Space Shuttle and ISS missions. This phase represents a significant amount of the preparatory infrastructural work in sustaining small scale operations, with the intention of upscaling in the future.

Phase 4: Basic Operations (2040 - 2060)

The "Basic Operations" phases defined by several roadmaps is characterized by the preliminary missions conducted and the long-term inhabitation of humans. Here, infrastructure, governance, and human aspects are described.

Phase 4 Infrastructure

Power and Distribution. In Phase 4 the need and capability to produce energy continuously is required due to the permanent inhabitation of the base. An increased number of solar energy collection facilities necessary. However, different approaches, like thermal Concentrated Solar Power (CSP) (Figure 4) and a power grid management system (PMS) must be taken to address the lack of sunlight during the lunar night and support Goal 12: Zero Waste [58].

Communication. Long-term human missions, and the likelihood of scientific missions being conducted on the far side of the Moon, could require scaling the capability and number of relay satellites within low lunar orbit. Lunar ground stations would also be prepared for future settlement growth, which would allow for large amounts of continuous data transfer.

Navigation. To support the robotic and crewed missions (6 to 10 astronauts) on the lunar surface to perform scientific experiments of 180 days, expansion of the navigation system and the ground-based lunar navigation system mentioned would be planned. This would reduce costs of satellite launches and their station keeping [58].

Transportation. In situ fuel generation, in the form of hydrogen and oxygen, may be synthesized from lunar polar ice caps to support fuel needs for crew rotation [59] (Goal 9: Sustainable Transportation, Goal 14: Sustainable ISRU). For surface transportation of crew and resources, electrically powered buses, with a pressurized operations cabins and threaded wheels, have been proposed [60].

In Situ Resources. Here, lunar resources primarily serves the purpose of sustaining a permanent human presence with a secondary commercial focus. This includes water extraction from lunar craters and regolith through heating, evaporation, and condensation processes [61].

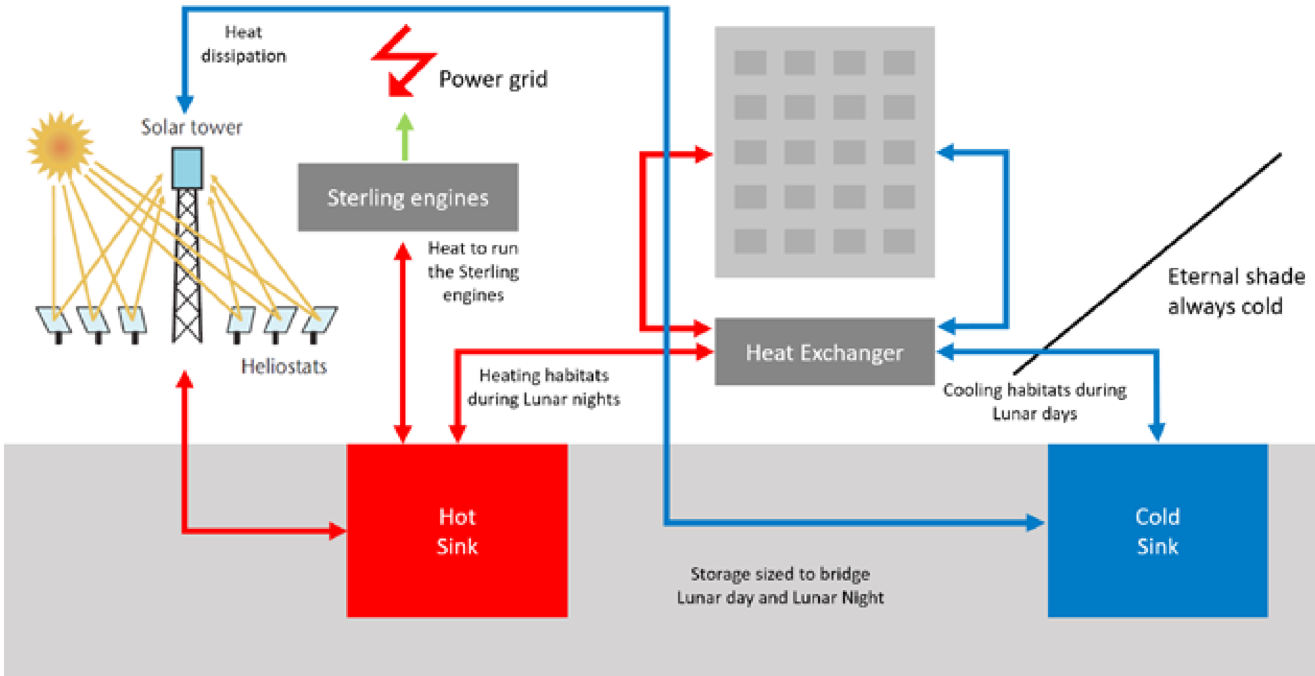


Figure 4. A CSP Tower system combined with heat and cold storage sinks

Phase 4 Governance

Here, lunar activities shift from development towards sustained, long-duration activities, an analog for which is the ISS. Therefore, an active governance model, similar to ISS, wherein ISS partners may extend their national jurisdiction onto their respective elements of the station [62], and wherein the agreed upon roles and responsibilities of all space actors and a management structure to control and govern activities, would serve to ensure that new activities follow international law on Earth, including ensuring that the Moon is used exclusively for peaceful purposes (including non-weaponization, a ban on military installations, as per the Moon Agreement, and ensuring actions of a non-aggressive nature). However, the inclusion of private companies, which fall under the jurisdiction of their registered state, would require a unique approach to this government level agreement.

Phase 4 Human Aspects

Here, the necessary changes in life support systems, medical procedures, and physical training required for successful completion of the phase are described.

Life Support. Here, open-loop LSSs transition to semi-closed-loop LSSs, with the goal being to achieve 95% closed-loop capability, similar to the ISS today [56]. Unlike the Phase 3 astronauts who were confined to their lander modules, EVA suits and vehicles with the portable LSS will be largely used for outpost activities. Phase 4 would rely on a future iteration of ESA's Advanced Closed Loop System to permit the survivability of the crew during the mission [63].

External Stressors. Important stressors to consider for long-duration lunar missions include (1) physiological (i.e., radiation, lack of natural time parameters, impacts to circadian rhythms, limited exposure to sunlight based on the lunar orbital period, ⅙ gravity), (2) psychological (i.e., isolation, mission demands, limited hygiene, interpersonal tensions, social conflicts), (3) mission factors (i.e., high workload, limited resources and communication, food limitations), and (4) habitability (i.e., limited privacy, constant noise/vibration). Mitigating against these stressors will serve to maximize crew productivity and mental health for the long term [64].

Medical Capabilities. Here, ⅓ of the crew would receive 34 hours of medical training, similar to ISS [65]. Familiarity with cardiopulmonary resuscitation, vascular access, and intravenous fluid infusion is required. Incorporating regular exercise into astronaut work will help them combat bone, muscle, and cardiovascular deconditioning [66].

Cultural Aspects. Long-term habitation in the same working and living environment causes factors of culture and work expectations to emerge. Schedule implementation is crucial to balance the work expected of the crew and their daily lives which contribute to their mental health and ability to perform tasks. This includes staging the working period to best fit crew capabilities and the needs of the mission [67]. Additionally, new tools are being explored, which could create frameworks to ease cross-cultural teamwork [68] to include smooth intercultural interactions [69].

Phase 4 Summary

The Basic Operations phase focuses on conducting scientific missions and long-term testing of life support systems for a future human society. The use of previously established habitats plays a crucial role along with the extension of power infrastructure to include thermal concentrated solar power. Existing frameworks of communication provide the link to successful mission operations on the lunar surface and for relays back to Earth. Continued use of the existing navigation system for astronaut surface navigation will meet the needs of extended missions. In orbit transportation will utilize the existing lunar ascent element, while the inclusion of alternative surface transportation, such as rovers and electrically powered buses provides direct access to the crew of remote areas. Finally, mass mining of polar ice and the collection of lunar regolith to produce elements such as liquid water and oxygen for habitat sustainability underly the entire basic operations phase. The transition to partially closed-loop life support systems and the inclusion of advanced medical training and equipment is essential for long-duration crews. Legislation is needed to address the allocation of lunar space and resources. Collaborations could allow cultural and technological growth for future multicultural settlements.

Phase 5: Lunar Settlement (2060 -)

This phase is characterized by shifting away from conducting lunar base missions and operations, and towards the act of living and spending one's life on the Moon, with self-sustaining capabilities being achieved as the phase progresses. This includes development of larger economic markets, in situ resource utilization.

Phase 5 Infrastructure

This phase's goals are to increase the capabilities of power and distribution, communication, navigation, transportation, and habitation to ensure the demand requirements for this larger base are met.

Architecture. Here, the lunar base will continue to grow, and develop into a settlement, populated by employees, mission operatives, and residents. The increased growth of the settlement population will increase the demand for habitable modules. Future iterations of the orbital platform started in Phase 3 would act as supporting infrastructure for the lunar surface and beyond [70].

Power and Distribution. The growing rate of people, systems, and power dependent activities will determine the needed size of power production, distribution, and storage needs. Helium 3, which is in abundance on the lunar surface, could address these needs through fusion [71].

Communications. Moon ground stations and Laser-Based Communication Systems would be further developed at this stage, enabling a more comprehensive communications line of sight. In addition, a Moon network communication system similar to a cellular network concept shall be considered [33, 72-73].

Navigation. Here, the establishment of a Lunar Navigation Satellite System, the lunar equivalent to a Global Navigation Satellite System, would be developed to ensure connectivity for daily life, similar to those present on Earth. This could comprise of a constellation of 16 CubeSats orbiting the Moon along two inclined circular orbits at an altitude of 33,400 km from the lunar surface [74].

Transportation. To accommodate the growing number of passengers traveling to and from the Moon, it is anticipated that large amounts of fuel production would be established on the Moon by this time. However, all referenced roadmaps failed to address establishing the capability of managing and storing large amounts of cryogenic fuel on the surface of the Moon for long periods. Furthermore, the need for advancement in rocket technology to utilize other alternative in situ resources as propellant is necessary to maintain the sustainability of lunar resources, in line with Goal 14: Sustainable ISRU.

Surface Transportation. Lunar Roving Vehicles would no longer be sufficient for the lunar community, so, existing concepts for electrically powered lunar busses

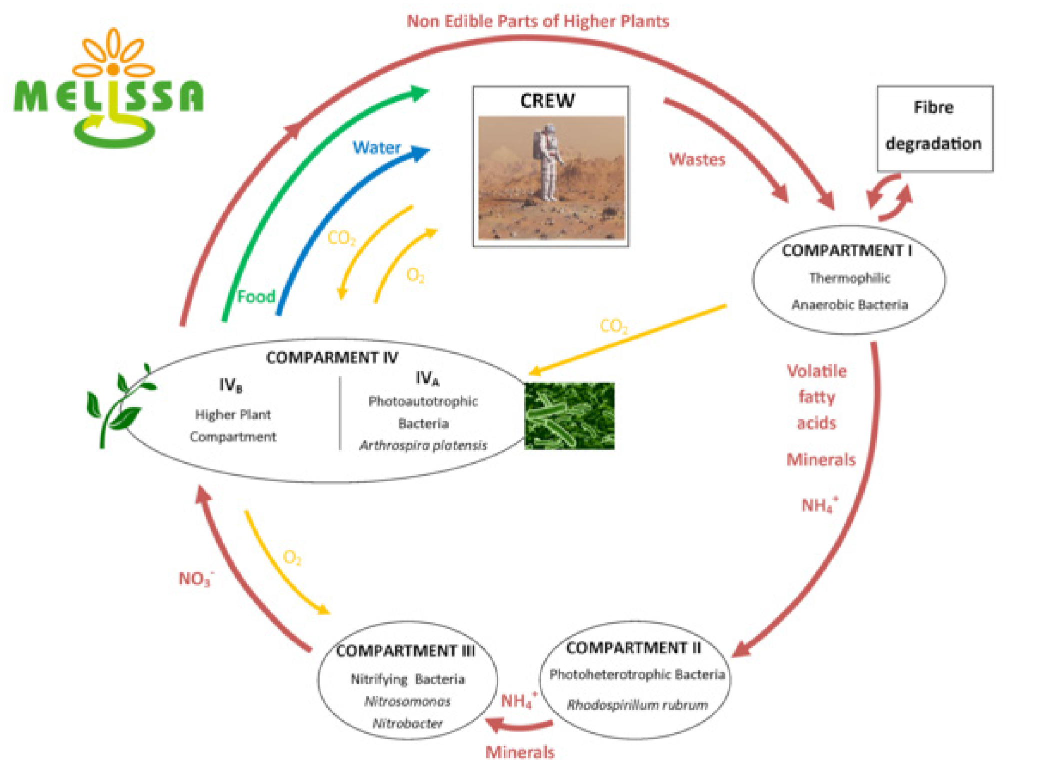


Figure 5. MeLISSA loop diagram [78]

and lunar railroads could be adopted for this phase and scaled appropriately to accommodate more people, but would require more initial investment in infrastructure [75-76].

In Situ Resources. With the increasing number of base inhabitants, the lunar regolith mining efforts should be expanded to meet the architecture and life support material requirements. Furthermore, to procure more hydrogen for the anticipated commercial fuel market demand, lunar ice water mining could be enhanced. To address the transportation needs of this phase, resources could be used to construct landing pads, roads, and railways.

Phase 5 Governance

The level of governance required for potential Phase 5 activities could be a subset of an existing body on Earth, and organized as an extension of the United Nations General Assembly and UNOOSA. The lunar population may evolve with its own cultures, activities, habits, and local laws, so establishing a new government entity on the Moon, with greater transparency of activities and customs, similar to the Kingdom of Asgardia, could become compelling [77]. Once activity becomes organic on the Moon, it may no longer be feasible or suitable, to assign responsibility to states on Earth for activity organically created on the Moon.

Phase 5 Human Aspects

To support the growing population of lunar residents, medical support would be provided widely, and combined with procedures to ensure the safety of human health. Here, LSSs and medical capabilities are addressed together with the cultural aspects that could evolve during the development of a settlement.

Life Support. Here, closed-loop LSSs (e.g., the Micro-Ecological Life Support System Alternative (MELiSSA), shown in Figure 5) would become increasingly important to provide sustainable food, oxygen, and water as the lunar settlement population grows. Among the roadmaps examined, Airbus, the Global Exploration Roadmap, and the National Space Society specifically emphasize the importance of evolving a settlement to become self-sustaining, however, most of the examined roadmaps do not contain fully developed closed-loop LSSs.

Medical Capabilities. Here, preventative measures, inhabitant selection processes, and emerging advanced medical capabilities are required for the progression of a full scale, growing human settlement. Telemedicine and telesurgery will be insufficient alone, so on site clinical and medical expertise will serve to mitigate any medical problems to avoid emergency flights to Earth. This includes on-site diagnostics, urgent treatment, preventative medicine, and a variety of pharmaceuticals must be available on the Moon during this phase and should include capabilities such as laboratory analysis, surgery, dentistry, sterilization, antibiotic treatment of infectious disease and mental health interventions, as well as simple clinical check-ups for inhabitants [79].

Cultural Aspects. During this phase, a unique lunar culture, similar to other isolated communities, such as Antarctica and the ISS, could emerge with new religious interpretations, new social norms influenced by lunar environment enabled technology, new teamwork models, new human-robotic systems, and new artistic pastimes [58]. Similarly, markets for lunar activities, such as entertainment, education, and tourism, could also increase. Rights and liberties of the future lunar base inhabitants, and what constitutes their rights to return to Earth may also become important concerns [80].

To address these cultural changes, several Lunar Sustainability Goals, specifically Open Access, Diversity and Opportunity, International Cooperation, and Standardization, are described above. Collectively, these goals work towards providing opportunities for a sustained international, intercultural presence on the Moon, in line with the vision of the Moon Village Association.

Phase 5 Summary

Many of the roadmaps reviewed for this paper conclude with this phase, wherein the lunar population is capable of leading sustained live, within the limitations of the Moon's environment. Infrastructure is expanded to support a larger population. Life support evolves to eliminate the need for resupply from Earth and medical care capabilities are expanded on-site to avoid emergency returns to Earth. Lunar culture may establish new religions, team models, and societal norms influenced by the lunar environment and cyber-physical, human-robotic interfaces will likely influence these. Finally, the internationality of the settlement invites interested organizations to collaborate for the sustainability of the mission and may lead to independent governance.

Conclusion

These five stages of lunar base development, as consolidated from the literature, provide a roadmap for a lunar settlement, maintained by a variety of actors (Table 3).

However, all plans reviewed fall short of establishing and emphasizing a sustainable approach to each phase of the process. To address these insufficiencies, the following phases for establishing a lunar base work to combine the operational details and phases of existing lunar evolution roadmaps, and add goals related to sustainability that can serve to protect the lunar environment and ensure the long-term sustainability of the lunar base, while supporting the rationales, outlined in IAC-19-D4.2.8 [1].

These 15 Lunar Sustainability Goals can be applied during mission planning throughout the lunar settlement process by a variety of actors. Further details, including targets and drivers for each goal, are available online at sustainablemoon.com

Phase	Focus	Primary Inhabitants	Outcome
1	Assessment of Lunar surface for usable resources and landing sites.	Remote sensing satellites. Ground based rovers and other robots.	Identification of potential habitat sites. Quantification and localization of resources.
2	Remote infrastructure and habitat preparation.	Remote controlled, autonomous robots.	Initial infrastructure for human arrival.
3	Finalizing infrastructure and habitat for future missions. Short duration surface missions.	Humans and robots.	Finalized infrastructure for permanent human habitation.
4	Conducting science-based missions.	Specialists (geologists, astronomers, astronauts, etc).	Preliminary technology development for future inhabitants.
5	Transition towards society on the Moon.	Lunar citizens and workers Space Tourists.	Self-sustaining lunar society.

Table 3. Summary of key elements and goals of each phase

Acknowledgements

Sustainable Moon was made possible through the advisorship of the following faculty and teaching associates at ISU: Volker Damann (Faculty Advisor), Danijela Stupar (Faculty Advisor), Ana Cristina Baltazar Garduño (Teaching Associate), Chris Welch (Program Director).

We recognize the following ISU faculty for their lectures and ideas in support of this project: Vasilis Zervos, Hugh Hill, Taiwo Tejumola, Gongling Sun.

We also thank the following external individuals and organizations for lending their inspiration: Robert Thirsk (University of Calgary), Stuart Eves (Surrey Satellite Technology Limited), Angie Bukley (The Aerospace Corporation), Jacques Arnould (France National Center for Space Studies (CNES)), Barbara Imhof (LIQUIFER Systems Group), Christian Stenzel (Airbus), Claudie Haigneré (ESA), Kathryn Denning (York University), Philippe Achilleas (Institut du Droit de l'Espace et des Télécommunications (IDEST)), Michael Waltemache (Ruhr-University Bochum), Kyle Acierno (ispace), Loïc Blaise (Polar Kid), Secure World Foundation, Moon Village Association.

References

[1] Incorporating Sustainability into Rationales for Lunar Settlement: Addressing Global Challenges through Lunar Sustainability Goals, IAC-19-D4.2.8, 70th International Astronautical Congress, Washington DC, United States, 2019, 21-25 October.

[2] Moon Express, Timeline. 2019, http://www.moonexpress.com/about-us, (accessed 30.01.19).

[3] Airbus, Sustainability Challenges on the Moon, International Space University, 2018.

[4] ispace, ispace 2040 Vision Movie. 2017, https://youtu.be/r7CW92i0z_o, (accessed 14.02.19).

[5] Lockheed Martin, Ahead of the Curve. 2018, https://www.lockheedmartin.com/en-us/news/features/2018/ahead-of-the-curve.html, (accessed 14.02.19).

[6] A. Boyle, Blue Origin targets moon landing by 2023 as step toward lunar settlement. 2018, https://www.geekwire.com/2018/blue-origin-targets-moon -landing-2023-early-step-toward-lunar-settlement, (accessed 14.02.19).

[7] SpaceX, Making Life Multiplanetary. 2017, https://www.spacex.com/sites/spacex/files/making_life_multiplanetary-2017.pdf, (accessed 14.02.19).

[8] B.H. Foing, The Moon: Next Steps for Science, Exploration & Utilization. 2003, http://sci.esa.int/nextstep/FoingMoon.pdf, (accessed 27.02.19).

[9] JAXA, Lunar Explorers Around the World. 2003, http://global.jaxa.jp/article/special/lunar/exploration_e.html, (accessed 14.02.19).

[10] NASA, Technology Roadmaps Introduction, Cross-cutting Technologies, and Index. 2015, https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_0_in roduction_crosscutting_index_final_0.pdf, (accessed 04.12.18).

[11] NASA, Technology Roadmaps TA 3: Space Power and Energy Storage. 2015, https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_3_space_power_energy_storage_final.pdf, (accessed 04.12.18).

[12] C. Lee, Korean Lunar Exploration Program: Current Status and Future. 2017, http://files.mai.ru/site/conf/aeroweek/4.%20Lee,%20Cahng%20Jin.pdf, (accessed 11.03.19).

[13] Sina, China's latest space exploration road map: Crewed moon landing in 2035, to visit Uranus in 2048. 2018, https://k.sina.com.cn/article_6477363539_18214b95300100f9ai.html, (accessed 14.02.19).

[14] ISECG, The Global Exploration Roadmap. 2018, https://www.nasa.gov/sites/default/files/atoms/files/ger_2018_small_mobile.pdf, (accessed 01.03.19).

[15] NSS, NSS Roadmap to Space Settlement (3rd Edition 2018): Part Three: To the Moon. 2018, https://space.nss.org/nss-roadmap-to-space-settlement-3rd-edition-2018-part-3, (accessed 14.02.19).

[16] ISU, Lunar Night Survival. 2018, https://isulibrary.isunet.edu/doc_num.php?explnum_id=1506, (accessed 08.03.19).

[17] J. Lalonde, A New Concept For A Lunar Settlement, International Space University, Master of Space Studies Program, 2018.

[18] United Nations, Academic Impact: Sustainability. 2019, https://academicimpact.un.org/content/sustainability, (accessed 10.03.19).

[19] UNOOSA, International Space Law: United Nations Instruments. 2017, http://www.unoosa.org/res/oosadoc/data/documents/2017/stspace/stspace61rev_2_0_html/V1605998-ENGLISH.pdf, (accessed 11.03.19).

[20] R.H. Dietz, D.E. Rhoades, L.J. Davidson, Apollo Experience Report - Lunar Module communications. 1972, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19720023255.pdf, (accessed 02.03.19).

[21] H. Li, C. Zhong, A machine vision based autonomous navigation system for lunar rover: The model and key technique, Sensor Review, 36 (2016) 377–85.

[22] B.F Kutter, G.F. Sowers, Cislunar-1000: Transportation supporting a self-sustaining Space Economy, in: AIAA SPACE 2016, American Institute of Aeronautics and Astronautics, Reston, Virginia, Reston, Virginia, 2016.

[23] NASA Science, NASA Announces New Partnerships for Commercial Lunar Payload Delivery Services. 2018, https://solarsystem.nasa.gov/news/774/nasa-announces-new-partnerships-for-commercial-lunar-payload-delivery-services, (accessed 18.02.19).

[24] J. Guo, C. Han, Design of Guidance Laws for Lunar Pinpoint Soft Landing, Advances in the Astronautical Sciences, 135 (2010) 1-13.

[25] NASA, Lunar Architecture. 2013, https://www.nasa.gov/pdf/140635main_ESAS_04.pdf, (accessed 06.03.19).

[26] H.R. Fischer, In-situ resource utilization feasibility of the use of lunar soil to create structures on the moon via sintering based additive manufacturing technology. Aeronautics and Aerospace Open Access Journal, 2 (2018), 243–48.

[27] C.A. Hemandez, S. Sunder, B. Vestgaard, Design of a Thermal and Micrometeorite Protection System For an Unmanned Lunar Cargo Lander. 1989, https://www.lpi.usra.edu/lunar/documents/NASA CR-190014.pdf, (accessed 12.03.19).

[28] H. Benaroya, L. Bernold, Engineering, Design and Construction of Lunar Bases, Acta Astronautica. 62 (2008) 277–99.

[29] B. Imhof, D. Urbina, P. Weiss, et al., Advancing Solar Sintering for Building A Base On The Moon. 68th International Astronautical Congress, Adelaide, Australia, 2017, 25-27 September.

[30] C. Ciardullo, M. Morris, K. Lents, et al., Mars Ice House: Using the Physics of Phase Change in 3D Printing a Habitat with H2O. 2016, https://ttu-ir.tdl.org/handle/2346/67606, (accessed 10.12.18).

[31] S. Potter, Demonstration Proves Nuclear Fission Can Provide Exploration Power. 2018, https://www.nasa.gov/press-release/demonstration-proves-nuclear-fission-system-can-provide-space-exploration-power, (accessed 04.12.18).

[32] L. Summerer, A. Cowley, K. Stephenson, et al., 2015. Power for Surviving the Lunar Night, ESA Options for Lunar Surface Power Systems. Presented to International Space University, Space Studies Program 2018 on 30.06.18.

[33] D. Coutinho, C. Welch, Interface Standardization for the Moon Village. In: 69th International Astronautical

Congress, Bremen, Germany, 2018, 1-5 October.
[34] ISECG, The Global Exploration Roadmap. 2018, https://www.nasa.gov/sites/default/files/atoms/files/ger_2018_small_mobile.pdf, (accessed 01.03.19).
[35] X. Ning, J. Fang, A new autonomous celestial navigation method for the lunar rover, Robotics and Autonomous Systems. 57 (2009) 48–54.
[36] A. Trebi-Ollennu, T. Huntsberger, Y. Cheng, E.T. Baumgartner, B. Kennedy, P. Schenker, Design and analysis of a sun sensor for planetary rover absolute heading detection, IEEE Transactions on Robotics and Automation. 17 (2001) 939-47.
[37] J. Amos, Jeff Bezos names big next rocket New Glenn. 2016, https://www.bbc.com/news/science-environment-37342181, (accessed 15.03.19).
[38] European Lunar Lander, Directed by spaceflight ESA, Erasmus. 2012, http://youbenefit.spaceflight.esa.int/we-explore, (accessed 12.03.2019).
[39] G.A. Landis, Materials refining on the Moon, Acta Astronautica. 60 (2007) 906–15.
[40] J.N. Pelton, A.P. Bukley, The Farthest Shore: A 21st Century Guide to Space. 2nd ed. Apogee Books, 2018.
[41] International Academy of Astronautics, Space Mineral Resources: A global Assessment of the Challenger and Opportunities, 2015.
[42] R.V. Rao, V. Gopalkrishnan, K. Abhijeet, Recent Developments in Space Law: Opportunities and Challenges. Springer, Singapore, 2017.
[43] Secure World Foundation, Handbook for New Actors in Space. 2017, https://swfound.org/handbook, (accessed 08.01.19).
[44] G. Daines, International Space Station Length and Width. 2014, https://www.nasa.gov/content/international-space-station-length-and-width/#.XHcOFohKiHt (accessed 27.02.19).
[45] A.S. Howe, B. Sherwood, Out of This World: The New Field of Space Architecture, American Institute of Aeronautics and Astronautics, Reston, 2009.
[46] D. Barlev, R. Vidu, P. Stroeve, Innovation in concentrated solar power. 2011, https://linkinghub.elsevier.com/retrieve/pii/S0927024811002777, (accessed 09.12.18).
[47] W. Lafayette, Putting Some Buzz Into Space Hotels. Space Daily, 2002, http://web.archive.org/web/20080509062142/http:/www.spacer.com/news/tourism-02b.html, (accessed 03.03.19).
[48] Z. Khan, A. Vranis, A. Zavoico, et al., Power System Concepts for the Lunar Outpost: A Review of the Power Generation, Energy Storage, Power Management and Distribution (PMAD) System Requirements and Potential Technologies for Development of the Lunar Outpost, 2006, http://large.stanford.edu/courses/2012/ph241/copeland1/docs/20060026085_2006208399.pdf, (accessed 14.02.19).
[49] NASA, Technology Roadmaps TA 3: Space Power and Energy Storage. 2015, https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_3_space_power_energy_storage_final.pdf (accessed 15.02.19).
[50] M. Wall, NASA Plans to Build a Moon-Orbiting Space Station: Here's What You Should Know. 2018, https://www.space.com/41763-nasa-lunar-orbiting-platform-gateway-basics.html, (accessed 27.02.19).
[51] J. Bridenstine, B. Gerstenmaier, Human Landing System BAA Industry Forum Agenda Topics Speakers NASA Affiliation Moon to Mars and Human Landing System (HLS) Remarks. 2019, https://www.fbo.gov/index?s=opportunity&mode=form&tab=core&id=13ca9566b575d496988122e66efc8230, (accessed 14.03.19).
[52] M. Baratta, G. Genta, D. Laurenzano, D. Misul, Exploring the surface of the Moon and Mars: What kind of ground vehicles are required? Acta Astronautica. 154 (2019) 204–13..
[53] R.D. Launius, Historical Analogs for the Stimulation of Space Commerce. NASA, Washington DC, 2014.
[54] P. Ehrenfreund, M. Race, D. Labdon, Responsible Space Exploration and Use: Balancing Stakeholder Interests, New Space. 1 (2013) 60-72.
[55] Final Report, International Moon Village Workshop, Strasbourg, France, 2017, 19-21 November.
[56] V. Damann, Environmental Control and Life Support Systems, HPS-M2-L12. International Space University, 2018.
[57] Smithsonian, Apollo 11 Command Module Medical Accessories Kit. https://airandspace.si.edu/collection-objects/kit-medical-accessories-command-module-apollo-11, (accessed 03.03.19).
[58] Sustainable Moon MSS19 Team Project Report, International Space University, Illkirch-Graffenstaden, 2019.
[59] R.M. Zubrin, The Design of Lunar and Mars Transportation Systems Utilizing Extra-Terrestrial Resources, Acta Astronautica. 32 (1994) 617–28.
[60] ASI, Lunar Surface Bus. 2007, http://www.asi.org/adb/02/12/08/Moonbus-1.html, (accessed 22.02.19).
[61] C.A. Arregoitia, R. Boileau, I.O. Coronado, et al., Full Moon Storage: Delivery of Oxygen and Hydrogen for Lunar Exploration, International Space University, Master of Space Studies Program Presentation, 2007.
[62] ESA, International Space Station legal framework. 2019, https://m.esa.int/Our_Activities/Human_and_Robotic_Exploration/International_Space_Station/International_Space_Station_legal_framework, (accessed 28.02.19).
[63] ESA, Advanced Closed Loop System. 2018, https://m.esa.int/Our_Activities/Human_and_Robotic_Exploration/Research/Advanced_Closed_Loop_System, (accessed 02.03.19).
[64] H. Benaroya, Building Habitats on the Moon, Springer, Switzerland, 2018.
[65] W. Zhang, Emergency medicine for commercial spaceflight. 2016, https://isulibrary.isunet.edu/index.php?lvl=notice_display&id=9812, (accessed 09.12.18).
[66] V. Damann, Muscle & Bone in Space, HPS-M2-L01. International Space University, 2018.

[67] V. Damann, Preflight Preparation and Fitness HPS-M2-L13. International Space University, 2019.
[68] A. Heimbüchen, When Cultures Meet: Modelling Cross-Cultural Knowledge Spaces, Information Modelling and Knowledge Bases. 166 (2008) 314–21.
[69] B. Rai, J. Kaur, Human Factor Studies on a Mars Analog During Crew 100b International Lunar Exploration Working Group, EuroMoonMars Crew: Proposed New Approaches for Future Human Space and Interplanetary Missions. 4 (2012), 548–57.
[70] ESA, What is the Deep Space Gateway? 2017, http://exploration.esa.int/Moon/59374-overview, (accessed 20.02.19).
[71] S. Dobransky, Helium-3: The Future of Energy Security, International Journal on World Peace. 30 (2013) 61-88.
[72] Vodafone Group, Vodafone and Nokia to create first 4G Network on Moon. 2018, https://www.vodafone.com/content/index/media/vodafone-group-releases/2018/vodafone-and-nokia-to-create-first-4g-network-on-Moon.html, (accessed 20.02.19).
[73] V. Kuroda, M. Allard, B. Lewis, M. Lindsay, Comms for Small Sats: The Lunar Atmosphere and Dust Environment Explorer (LADEE) Communications Subsystems. In: 28th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, 2014, 4-7 August.
[74] A. Batista, E. Gomez, H. Qiao, K.E. Schubert, Constellation Design of a Lunar Global Positioning System Using CubeSats and Chip-Scale Atomic Clocks. 2012, https://pdfs.semanticscholar.org/a0c1/78f482d3037adf70be94b47ac20088a54fd5.pdf, (accessed 07.03.19).
[75] D. Schrunk, B. Sharpe, B.L. Cooper, et al., The Moon: Resources, Future Development and Settlement. Praxis, New York, New York, 2007.
[76] L.E. Bernold, Cable-Based Lunar Transportation System, Journal of Aerospace Engineering. 7 (1994) 1–16.
[77] Asgardia, Constitution of the space kingdom of Asgardia. 2017, https://asgardia.space/en/page/constitution#c8-a33, (accessed 20.02.19).
[78] ESA, MELiSSA: Closed Loop Compartments. 2015, https://www.esa.int/Our_Activities/Space_Engineering_Technology/Melissa/Closed_Loop_Compartments, (accessed 15.02.19).
[79] L.H. Stewart, D. Trunkey, G.S. Rebagliati, Emergency Medicine in Space, The Journal of Emergency Medicine. 32 (2007) 45-54.
[80] K. Denning, Space and Anthropology, M2-HUM-L2. International Space University, 2018.

IAC-19, E1,IP,2,x52268

Preparing Students for the International New Space Economy

Nathaniel Woodford[a], Idris Motiwala[b]

[a] *Legal Department, Firefly Aerospace, Inc. 1320 Arrow Point Dr. Ste. 109 Cedar Park Texas, 78613 USA, Nathaniel.woodford@firefly.com*
[b] *Legal Department, Firefly Aerospace, Inc. 1320 Arrow Point Dr. Ste. 109 Cedar Park Texas, 78613 USA, Nathaniel.woodford@firefly.com*

Abstract

Firefly Academy, Inc. is a Private Operating Foundations dedicated to giving students practical experience in the commercial space industry. As the space industry becomes more commercialized, students entering the workforce are going to have increasing opportunities to enjoy careers in commercial space companies. However, recent graduates of undergraduate programs often lack the hands-on skills and experience to let them excel in commercial space companies. To better prepare students to succeed in the commercial space companies, and to help them becomes drivers of innovation and change, incorporating non-traditional, practical programs into traditional education courses is necessary. This paper looks at the approach taken by the flagship company-university partnership initiative undertaken by Firefly Academy, in partnership with Firefly Aerospace, Inc. and the University of Texas. to illustrate the benefits of an interdisciplinary, project-based approach to educating students which combines initiates from the schools of engineering, law, policy, and business as a model for future curriculum enrichment initiatives for other undergraduate students. The flagship program is designed around a corporate-university collaboration facilitated by a non-profit entity. First, the students are given a practical, commercially applicable goal of launching a student-made rocket above the Karman line (100km). Working on this project, whether successful or not, provides real world experience of the technical problems and issues many space start-ups face in the design and development of new technology. Second, the initiate utilizes corporate resources from a private company to provide mentorship, expertise, facilities, and funding to provide the resources the students need to work on and complete the project. The project will span multiple years and involve students from many engineering disciplines. Students can engage in the project both as a class or as a club. The curriculum of both covers a broad range of topics and practical problems faced by commercial companies in the Research & Development process, including engineering, business, compliance, and regulatory issues faced by companies. At first the education will be focuses primarily on technical concepts necessary for the design and building of a rocket but will eventually include compliance and business curriculum as well as students from other disciplines. By giving students a problem to solve which mirrors the issues face by commercial space corporations, and combining an interdisciplinary curriculum with commercial partnerships, students can be better prepared working in the commercial space industry. The success of the program will be measured by the achievement of project goals, the number of students involved, and the percentage of students who matriculate to successful employment post-graduation. As the program proceeds, Firefly Academy will expand its partnerships to other universities, using lessons learned from the flagship program.

Acronyms/Abbreviations

Research and Development (R&D)
Chief Executive Officer (CEO)
Texas Rocket Engineering Lab (TREL)
The University of Texas Austin (UT)
Science, Technology, Engineering, and Mathematics (STEM)
Rocket Engineering Practicum (REP)
Preliminary Design Review (PDR)
Critical Design Review (CDR)
Flight Readiness Review (FRR)
Computer Automated Design (CAD)
Commercial off the Shelf (COTS)
Human Resources (HR)
Huston Tillotson University (HTU)
Firefly International Rocket Event (FIRE)

"If America fails to grow more STEM talent over the next few years, our country risks being left behind technologically. That's why Firefly's challenge is so important. Inspiring young people and making science cool is the name of the game."[1]

1. Introduction

Firefly Academy, Inc. is a Private Operating Foundation dedicated to giving students practical experience in the commercial space industry. As the space industry becomes more commercialized, students entering the workforce are going to have increasing opportunities to enjoy careers in commercial space companies. However, recent graduates often lack the hands-on skills and experience to let them excel in commercial space companies. To better prepare students to succeed in industry, incorporating practical experience programs into traditional education courses is necessary. This paper looks at the approach taken by the flagship company-university partnership initiative undertaken by Firefly Academy, in partnership with Firefly Aerospace, Inc. and the University of Texas, to illustrate the benefits of an interdisciplinary project based approach to educating students in practical rocketry skills. This program combines initiates from the schools of engineering, law, policy, and business as a model for future curriculum enrichment initiatives for other undergraduate students.

The flagship program is designed around a corporate-university collaboration facilitated by a nonprofit entity. First, the students are given a practical, commercially applicable goal of launching a student-made rocket past the Karman line. Working on this project provides real worldvexperience of the technical issues many NewSpace startups face in the design and development of new technology. Second, the initiative utilizes corporate resources from a private company to provide mentorship, expertise, facilities, and funding to provide the resources the students need to work on and complete the project. The project will span multiple years and involve students from many engineering disciplines. Students can engage in the project both as a class or as a club. The curriculum covers a broad range of topics and practical problems faced by commercial companies in the R&D process, including engineering, business, compliance, and regulatory issues.

At first the education will be focused primarily on technical concepts necessary for the design and building of a rocket but will eventually include compliance and business curriculum as well as students from other disciplines. By giving students a problem to solve which mirrors the issues face by commercial space corporations, exposing students to multiple disciplines, and engaging in strategic commercial partnerships, students can be better prepared to work in the commercial space industry. As the program proceeds, Firefly Academy will expand its partnerships to other universities using lessons learned from the flagship program.

2. Firefly and the Problems of the NewSpace Economy

Firefly Aerospace is part of the emergence of NewSpace companies dedicated to growing the space economy of the coming decades. Firefly wants to make space for everyone by providing reliable and cost effective access to space with a steady launch cadence serving payloads in the small to medium class of under 4000kg. One of the major limits of the growth of economy in space is cost of access. Until relatively recently, the cost of launch has limited the space economy to government missions. With the advent of SpaceX and similar companies, space has proven to be profitable. Firefly is focused on reducing the cost of access to space by focusing on developing smaller, less expensive launch vehicles using lighter, modern materials, and innovative, simple designs to lower the cost of production and launch.

In ramping up its commercial efforts to design, test, build, and launch the next-generation of small-launch vehicles, Firefly has encountered a fundamental problem: a dearth of talent in the workforce required for success in the NewSpace economy. Put simply, there are not enough qualified or experienced professionals in any age group to fill the needs of the NewSpace economy. Firefly is always short on the requisite manpower and is constantly looking for qualified people to add value to the organization. The challenges facing Firefly are twofold: First, simply finding people with the right skills and experience, and second, competing with other NewSpace companies to attract those people.

Access to space has historically being controlled by governments. As such, the skills, knowledge, and experience necessary for launching objects into space is concentrated in the minds of a small number of senior industry experts. Further, that knowledge is not widely disseminated among younger professionals. This scarcity of expertise creates an intense competition for the best talent in the field, for both new and experienced employees. The competition in turn raises overhead costs of finding, hiring, and retaining talent for key positions. Key roles may go unfilled for months because experienced or qualified candidates cannot be found, or competitors win them over. At best, this scarcity raises the cost of getting to space. At worse, it threatens the ability of the NewSpace economy to grow as a talent scarcity results in higher costs and a slowdown of research, development, and commercialization. Recognizing this problem, Firefly established Firefly Academy.

3. Enter Firefly Academy

Firefly Academy was conceived by Firefly's CEO, Dr. Tom Markusic, as a way to get university-aged students involved in the space economy earlier in their education. The acceleration of the NewSpace economy has created a generation of students excited about space but lacking the experience or skills necessary to be effective upon entry to the job market. There is a mismatch between the energized new generation with fresh ideas, and the old guard committed to doing space the way it has always been done. To bridge that gap, Firefly Academy was created as an independent nonprofit, partnering with Firefly Aerospace to provide students with mentorship and practical experience in space economic activities to develop the next generation of space industry experts to service the NewSpace economy.

As a 501(c)(3) nonprofit private operating foundation, Firefly Academy can bridge the gap between the private space sector and students and educational institutions. Its flagship program, the Texas Rocket Engineering Lab at the University of Texas Austin (TREL) provides students a hands-on education in rocket design. Firefly Academy is also funding TREL's participation in the Base-11 Space challenge. The Base 11 Space challenge is a competition for university students to design, build, test, and launch a rocket to an altitude of 100 km or more by the end of 2021 for a $1 million cash prize. [2] In order to be competitive, students need access to resources, infrastructure, and expertise that the private space sector can provide. The Base 11 Space Challenge presented the perfect opportunity for Firefly Academy to put its goals into practice by funding TREL's participation, facilitating access to Firefly Aerospace facilities and employees as support, and providing both a theoretical and practical education to students in the design, build, test, and launch of a rocket.

Firefly Academy, as the nonprofit branch of a corporation, has at its disposal both the resources and expertise to bridge the gap between industry and educational institutions. Firefly Academy can give energized and motivated students access to industry, where they can gain the skills and experience necessary to become the next generation workforce of the NewSpace economy. The next sections of this paper describe how Firefly Academy achieves this and lays out the vision for how the corporate-nonprofit partnership model may be applied in other contexts to provide a practicum-based education for the next generation workforce of the NewSpace economy.

4. Corporate-University-Nonprofit Partnership Structure

Firefly's goals of furthering STEM education and preparing workforce-ready students is made possible through a three-way partnership between Firefly Aerospace, Firefly Academy, and The University of Texas at Austin. Firefly Aerospace had four primary projects in mind when creating Firefly Academy:

Funding university rocket labs and aerospace engineering programs;

Providing guidance and expertise to teams of university students to build and launch their own rockets;

Building interest in STEM and aerospace programs beyond the Department of Aerospace Engineering and Engineering Mechanics; and

Funding and coordinating internships for students with NewSpace companies.

These goals may only be realized when Firefly Aerospace, Firefly Academy, and The University of Texas enter into relationships with each other. These relationships allow students not only to take advantage of corporate funding, but to also to build relationships with mentors and spend time collaborating in the operational environment of a NewSpace company. Given this experience, students graduate from university with the immediately-applicable skills and knowledge of a second or third-year engineer.

Each entity in this partnership benefits from the relationships it establishes. These benefits are outlined in Figure 1.

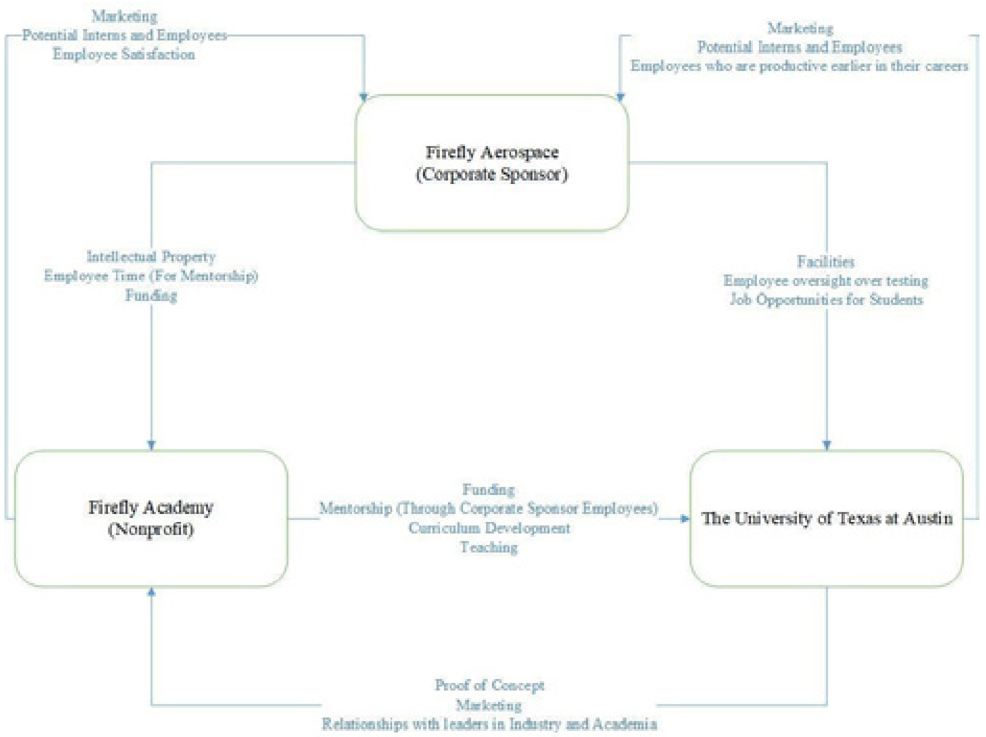


Fig. 1. Outline of the three entity partnership and the benefits to each.

AD ASTRA – IAC Special Issue – 2019

Although the initial costs of setting up these relationships are high, the ongoing benefit to each entity makes such an investment worthwhile. Firefly Aerospace benefits from better applicants, higher employee morale, and marketing opportunities. Firefly Academy benefits from funding, proof of concept to expand, intellectual property licensing, and proven relationships with experts in industry and academia. The University of Texas (UT) Austin benefits from funding, better facilities, curriculum development, and job opportunities and mentorship for students. This three-way partnership is essential to developing a strong NewSpace economy. Other companies can model partnerships using Firefly Academy as an example. Firefly Academy is also open to using its expertise in building similar relationships with other corporate sponsors and universities, without the need for a new nonprofit corporation to be incorporated for each relationship.

5. Firefly Academy's Activities to Date

5.1 The Flagship Program – Texas Engineering Rocket Lab

Firefly Academy established a relationship with UT towards the end of the 2018 Spring Semester. The initial meeting was with the head of the Department of Aerospace Engineering and Engineering Mechanics and student members of the Longhorn Rocketry Association. The students and professors at UT were very excited to work with Academy and have the opportunity to be the first University to launch a rocket past the Karman line (100 km).

Legally defining the relationship with UT took the most effort. UT, like most universities, is a large, slow moving establishment with multiple departments. Firefly Aerospace is a NewSpace startup and moves quickly in order to realize its goals of launching its first rocket and starting to become revenue positive. The difference in the relative work speeds of the two entities caused some frustration amongst Firefly leadership. This is a barrier that other companies should be ready to face. The development of the contractual framework to ensure funds were maximized in developing this rocket design program took all of the Summer and part of the Fall semesters. In these contracts, Firefly Academy agreed to donate up to one million dollars for the development of a rocket engineering lab and class at UT. Once the contracts were signed, in September 2018, the first installment of $250,000 was sent to UT.

From September to December 2018 Firefly worked with UT to develop a curriculum so that a course, the Rocket Engineering Practicum (REP), would be ready for students in January 2019. This quick development was a surprise to Firefly as Firefly was initially told that a course likely would not be offered until the fall semester of 2019. To date, TREL has an established design space at UT's main campus and a hardware development and test space at UT's Pickle Research Center. Firefly and UT are currently discussing a lease space at Firefly's test facility for TREL to perform the more hazardous tests of their engine designs.

5.2 Teaching and Mentoring

REP started in January 2019. REP was added as part of UT's Studies in Aerospace Engineering Course which, with continued funding for hardware, is sustainable for at least four more years. The curriculum was designed by UT in collaboration with Firefly Academy. REP consists of two lectures a week, with one lecture taught by UT staff, and the other taught by volunteers from Firefly Aerospace. The students reach out to Firefly lecturers after their lecture if they need any assistance or mentoring in the areas in which that person is an expert.

Firefly Academy is currently helping to facilitate the UT lease of a test cell at Firefly Aerospace's test site. Additional teaching and mentoring for the students is built into the lease for students' education and safety. The students will be required to go through design reviews with Firefly Aerospace directors before a test is allowed to be run. The standard aerospace testing cycle requires a design to go through a Preliminary Design Review (PDR), Critical Design Review (CDR), and Flight Readiness Review (FRR). The students will be required to contact the relevant director at Firefly in order to get these reviews of their designs. A PDR will be required before any tests are run. Finally, all tests will require final approval from the Firefly Director of Test. These reviews expose the students to real-world requirements and standard practices while giving them the opportunity to work with senior engineers who have risen to director level positions. Such exposure accelerates the student's professional development.

Finally, Firefly Academy has organized multiple activities for the students to visit Firefly Aerospace's headquarters. This has resulted in additional awareness among Firefly employees, who have volunteered their time outside work hours to mentor student both with their rocket design and with general career advice. Many times, engineers who leave Firefly Aerospace for other opportunities continue their mentoring relationships with these students, creating a more diverse network of mentors. It is Firefly Academy's goal to increase the mentor pool outside of Firefly Aerospace to provide the students a large and diverse pool of mentors. These mentor-mentee relationships will benefit these students for years to come.

5.3 Internships

Firefly Academy coordinated with Firefly Aerospace to provide twelve students with 3- month internships with Firefly Aerospace in the Spring Semester. Firefly Aerospace had only one intern in the spring semester that it did not find through Firefly Academy. For the Summer of 2019 Firefly Aerospace accepted 17 interns, most of which were from UT through Firefly Academy. Participation in Firefly Academy definitely gives students a leg up in the hiring process. In their three months at Firefly, these interns developed experience with designing parts in Autodesk Inventor (CAD), contacting and interacting with vendors for raw materials and COTS parts, and the assembly and integration of components. Not only does this experience help the students with their goal of building a rocket at TREL, but it helps these students find post-graduation employment. After proving the concept that participants in the Firefly Academy-sponsored TREL program and internships are better prepared for working in NewSpace companies, Firefly Academy will begin seeking other NewSpace partners to provide internships with more companies than just Firefly Aerospace.

5.4 Encouraging Entrepreneurship (Cross-Disciplinary Education)

As Firefly Academy was established, it began looking at a cross-disciplinary approach to its educational programs. Engineers seldom work in a vacuum. A successful business requires accountants, salesmen, procurement specialists, lawyers, HR, and many other administrative functions. Engineers must understand how to interact with these business functions in order to succeed in the business world. Firefly believes that helping students prepare for these interactions is key to their success in the professional world, and in preparing future NewSpace Entrepreneurs.

TREL's engineering students are exposed to students from other disciplines and backgrounds by including students from other disciplines in TREL, either as students enrolled in the REP class or as participants in TREL as an extracurricular club. There are currently three avenues Firefly is using to include such students in TREL:

- Firefly Aerospace attorneys are teaching a law school class aimed at preparing law students to practice law in a NewSpace company. These students may participate in TREL as a student organization, supervised by Firefly Aerospace's legal department.
- REP is going to be cross-listed with other UT schools in order to encourage participation. REP has already received applications from students in the McCombs School of Business.
- TREL encourages students from Huston-Tillotson University (HTU) to participate in the program. HTU is listed as an historically black college and university and is focused on providing working adults access to higher education. [3] Giving minority students access to STEM education through Firefly Academy is extremely important as students from both schools have the opportunity for be exposure to students from different cultural and socio-economic backgrounds. This valuable exposure can be mind- expanding and provide the type collaboration experiences that lead to entirely new innovations. Firefly Academy and UT initially attempted to include HTU students in the REP class, but HTU students were not able to balance the hours requirement of REP with their other classes and jobs needed to provide for their families. Firefly Academy and UT are looking into a paid internship program for HTU students to reestablish HTU participation in TREL.

5.5 Other Educational Programs

Firefly Academy and Firefly Aerospace collaborated to host the first annual Firefly International Rocket Event (FIRE), funded by Firefly Aerospace. Both US and international teams competed in a model rocket contest, with participation from local Texas middle schools. All of the teams built and launched model rockets at Firefly Aerospace's test facility in Briggs, Texas. School officials were impressed and shared Firefly's hope that this hands-on approach would spark an interest in STEM fields. The FIRE event was successful in this regard, with one student commenting that the fun was in "watching the rocket go up and feeling satisfied that you built it and now it's in the air," and another saying he hopes to work at SpaceX or Firefly in the future.

These two entities also collaborated in sending Firefly Aerospace CEO and Firefly Academy Director, Dr. Tom Markusic to the annual meeting of the Texas Boy Scout Councils to lead a discussion about NewSpace with over 300 Boy Scouts. At this meeting, Dr. Markusic also demonstrated Newton's Laws of Motion using a Firefly rocket gun and skateboard, which served to increase interest from the scouts towards Firefly and other space companies.

These small projects, while not as grandiose as the flagship project, are key to advancing the goals of Firefly Aerospace, Firefly Academy, and The University of Texas. Firefly Academy is advancing its goals towards increasing STEM education; the University of Texas advances its education goals and receives more applications to its competitive aerospace engineering program; and Firefly Aerospace is investing in future rocket scientists, who will help grow the NewSpace economy and Firefly Aerospace. Note that although UT is not directly involved in these educational outreach programs, it benefits from STEM outreach and development performed by Firefly due to its proximity, excellent academic reputation, and its close relationship with the two Firefly companies.

6. Principles for Application Beyond Firefly Academy

The fundamental problem of sustaining the growth of the NewSpace economy is staffing the workforce of the expanding economy. As a start-up whose speed and profitability depend on the quick expansion of a skilled, young workforce, Firefly recognizes this fundamental challenge. Since the knowledge necessary to train the next generation is concentrated in the hands of relatively few experts, Firefly Academy believes the most effective way to train the next generation is to form key partnerships between industry stakeholders and educational institutions in order to seed the next generation with the knowledge and experience they will need to excel.

Based on Firefly Academy's experiential model, Firefly believes there are four fundamental principles which can be applied to train the next generation of the space economy workforce.

1. Partnership
2. Leadership
3. Entrepreneurship
4. Outreach

6.1 Partnership

The Partnership principle promotes the formation of cooperative relationships between industry and educational institutions to develop programs to train students at the high-school and college level in order to instill in them the skills necessary to succeed in the NewSpace economy. NewSpace companies have an interest in training skilled workers prior to entering the workforce because many of skills which employees apply everyday are not trained in the traditional educational setting. Instead, these skills are better trained on the job or in a practical setting. Industry has the resources, expertise, and facilities to create practicum-based educational programs which provide students to learn essential skills while still in school. Firefly achieved this through forming its nonprofit branch, Firefly Academy, which in turn formed a partnership with the University of Texas Austin to establish TREL. Other companies can pursue similar partnerships. The students involved in such programs benefit from practical education, while the companies benefit from training interns and students who may become full-time employees. Such partnership programs can help NewSpace companies create pools of qualified workers with prior experience in the industry.

Beyond the industry-educational institution partnership, Firefly Academy also exhibits how forming partnerships between nonprofits and other companies can create opportunities beyond single-program endeavors. NewSpace companies like Firefly need qualified pools of candidates to fill jobs in order to grow economically and become profitable. However, while these companies have the facilities and experience to benefit students, often they lack the resources or bandwidth to lead such programs. Here, nonprofit entities like Firefly Academy can fill the gap by providing program management for both companies and educational institutions in return for funding and cooperation from NewSpace companies. Nonprofit entities also have the ability to fundraise from private donors and so can provide an additional source of program funding and cost savings. Using Firefly Academy as a model, other companies and institutions can form similar strategic partnerships to train the next generation of the NewSpace economy workforce.

6.2 Leadership

The Leadership principle suggests that industry must take on the responsibility for training the next generation of space workers. As stated previously, the concentration of space industry expertise means that the dissemination of knowledge will be largely downward vertical, instead of horizontal for the foreseeable future. The current landscape of industry expertise in the space economy is largely concentrated in the hands of current and former government employees and some heritage space companies. The demand for these professionals has not changed much until recent years. With the growth in the number of NewSpace companies, there is now more demand for talent than the current workforce can supply. In order to meet the challenge of staffing the growing numbers of open positions, industry leaders will need to invest in training the next generation and lead the dissemination of expertise from heritage industry to new workforce entrants. Forming strategic partnerships across industry which focus on developing programs to train the next generation can help grow the NewSpace economy with the next generation at the helm.

6.3 Entrepreneurship

The Entrepreneurship principle focuses on the need for crossdisciplinarity education. NewSpace companies obviously need engineers and other STEM graduates, but they also need accountants, salesmen, procurement specialists, lawyers, HR, and many other administrative functions. NewSpace companies are not just science projects, they are fundamentally businesses. It is not only technological advances that are driving the expansion of the space economy, but the demonstration that space companies can turn a profit. Neither the technology, nor the business, exist in a vacuum, especially in the world of NewSpace startups. Engineers must understand how to interact with these business functions in order to succeed in the business world, and business types need to understand the technology. If either set lacks a functional understanding of the other, it can paralyze a company's operations and lead to slow-down or inefficiencies. For example, if an engineer does not understand the company's business model or principles, they may spend unnecessary time working on an unprofitable technology. Likewise, if a business employee does not understand the technology, they may form a contract which is unperformable. This is why, from the outset, Firefly Academy has emphasized an entrepreneurial focus in its educational programs. REP students are not just taught engineering principles, they are also taught the law, policy, and business of NewSpace companies, and our law students are not just taught law, but also the basics of rocket technology and business considerations. When we talk about educating the workforce of the NewSpace economy, we are not just talking about STEM, but about educating students in across disciplines in order to train a NewSpace workforce which think and solve problems within the context of the business world.

6.4 Outreach

Finally, the Outreach principle emphasizes that to expand the pool of space-qualified professionals, industry must extend STEM assistance to students beyond its current or usual limits. There is a lot of excitement about space and its economic future right now because space is cool again. Everyone wants to be the next Elon Musk because space has once again captured our imaginations. There is a lot of energy and interest out there, but because space expertise has been government-controlled for so long, many young, smart, and talented people have no idea how to begin working in space. In order to build and maintain the current excitement, and to connect the next generation with industry experts who can train and mentor them, NewSpace companies should look into developing outreach programs to build excitement and begin recruiting the next generation. Bringing students to test or launch facilities or engaging them in fun activities can inspire them to pursue STEM education. Likewise, reaching out to older students in high-school and college to make them aware of internships and mentorship opportunities can help create excitement about working in the NewSpace economy and inspire them to work in this industry. Creating outreach opportunities which connect students early can give them an end-goal, a vision, and a passion for space which drives them to create the next big thing in this thrilling industry.

7. Conclusion

The Firefly Academy model emphasizes Partnership, Leadership, Entrepreneurship, and Outreach as a way to address the need-gap between essential positions and the available work- force supply. On the small scale, this may seem a micro-problem particular to a single NewSpace company, but on the macro-scale, the problems faced by Firefly evidence a lack of space-qualified industry workers to help drive the next generation of economic growth in space. Failure to address this gap, at best slows down economic growth, and, at worst, may threaten the long-term viability of the space economy. Without a workforce which can guarantee regular and affordable access to space, many of the most interesting and exciting space ventures may never get off the ground. A broad effort at collaboration between industry, nonprofits, and educational institutions, led by industry expertise and resources, and which focuses on training well-rounded students to meet the economic needs of the NewSpace economy may be the best way to address this problem.

These partnerships are not easy to form. Companies must navigate issues of liability, safety, non-disclosure, safety, intellectual property, and export compliance. The example of Firefly Academy proves that beneficial programs and partnerships can be successful in practice, despite these challenges. In time, with more resource investment, Firefly Academy will expand its partnerships and programs to other companies and universities. Just as TREL is Firefly Academy's flagship program, Firefly Academy may become the flagship for corporate-nonprofit-education partnerships to launch the next generation of space technology and space business experts.

References

In the text

Indicate references by number(s) in square brackets in line with the text. The actual authors can be referred to, but the reference number(s) must always be given.

Example: "..... as demonstrated [3,6]. Barnaby and Jones [8] obtained a different result ...."

List of references

[1] Deborah James, former Secretary of the U.S. Air Force and current member of the Firefly Advisory Board; see http://www.spaceref.com/news/viewpr.html?pid=54195
[2] http://base11spacechallenge.org/
[3] https://www.htdegrees.com; https://htu.edu.

IAC-19, E1,IP,7,x1249

Space Science and Technology: The Future of Girls/Women in Africa

Iroka Chidinma Joy

Women in Aerospace Nigeria (WIAN)/National Space Research and Development Agency (NASRDA), NIGERIA
sikechidinma@yahoo.com

1. Introduction

In many parts of the world, child education is a major challenge. Countries in Africa, as with most developing nations, have this problem, and the girl child is the worst hit. Most troubling is the low girl child involvement in Science, Technology, Engineering and Mathematics (STEM). Taking Nigeria as a case study, a report by UNESCO in 2014 stated that over 5.5 million girls were out of school. In addition, the National Population Commission in Nigeria stated in 2009 that more than 40% of the total female population has never been to school. Also, the same UNESCO report in 2014 indicated that the net enrollment rate for girls at primary school level stood at 56%. Out of the girls enrolled into school, very few of them eventually take up STEM. This is because of some preconceived and still dominant myths in the African society that have promoted an unhealthy fear of STEM. These myths pose a great challenge and must be overcome to set the girl child on the path to educational recovery.

2. The myths and the challenges they pose

There are two (2) dominant myths. These are:

2.1. The subjects of Science and Technology are difficult for a woman to handle.

I come from a country where girls are not encouraged to study STEM courses especially engineering because it is perceived to be a male dominated course and as such involves a lot of technical skills. If Nigeria was to be running engineering courses the way it should, like a hands-on practical approach, it would have been easier for the girls to venture into studying STEM and the related courses because they believe in and do very well with what they see, so I would say that there is little attraction in STEM for girls.

Again, there are no helpful strategies to boost the interest of these girls both from their teachers at school and family members at home. Recently in the course of my awareness creation in some secondary/high schools in FCT, Abuja Nigeria, I came across some girls that have not heard about space science and technology let alone the entrance courses. This informed me that there is a lot of work to be done in Nigeria and Africa at large. This made me ask a question in the class about those that would want to go into studying science and engineering and their response was quite discouraging as 25% of the girls did not raise their hands. I began to wonder why; some girls gave these myths as their reasons.

i. My mother said that engineering is not for girls.
ii. Having few girls in a class dominated by boys, their level of exposure will increase negatively.
iii. She also said that girls that make their career in engineering hardly keep their homes in marriage as their level of exposure would make them challenge their spouses.
iv. Again, you hardly get a job that will help you take care of your personal need.
v. The girls in engineering classes tend to be molested by their male teachers and even colleagues, etc.
vi. We have other factors like the social, culture and religion.

From my personal experience, I would say that their mothers are not far from the truth. In Nigeria and other developing countries, we have NGOs that promote STEM but a lot of them do it for their own benefit without truly caring about the situation on ground. They have no real desire to acquire the expertise required to tackle the problem. Most of them lack an action/activity roadmap and a truly measureable performance review based on funds generated for their operations.

Yes, since it is perceived that STEM is a masculine field or career, when in class/workshop, the teacher would always prefer the boys to do the hands on practical/experiments and write the reports as well, while the girls will only participate as spectators. I was a victim until one day while watching the boys interchange in each practical session at the workshop, I burst into tears. My teacher walked up to me and asked why I was crying, I told him, Sir, I can do all these things as well. Fortunately, I was given an opportunity to try and surprisingly I did as well as the boys. To be frank, from that day, my confidence was boosted and I became an encouragement to the other girls in class.

2.2. That the work environment in Science and Technology is challenging for a woman who seeks to be married

In most African traditions – as with many parts of the world – marriage is the hallmark for a woman. This idea automatically stimulates parents and teachers to stir the girls towards non-science oriented courses so they can fit into the society. This need to fit into the culture and society around you hampers the girls' ability to see herself as capable of overcoming any challenge posed by the subjects in STEM.

3. Overcomimg the challenge

While there are lots of misleading factors that stop girls from studying STEM courses such as lack of interest, economic, social, religious factors etc. These factors draw their strength from the two challenges identified above. Overcoming these challenges would require a concerted effort from parents, society, and government. One may ask, what role can these parties play to address these problems and debunk these myths? I start my solution with a story of my personal experience.

I personally overcame these myths with the help of my father who did not only bring a home teacher but also did not subscribe to this line of thinking that a career in science or engineering was solely for men. Instead he encouraged me to read wide and discover myself. On one of my visits to the local library, I came across an article on Katherine Johnson, the first African American woman to work on the Project Mercury and Apollo missions. This encounter informed me that I could feature prominently in the science community if I worked hard enough. Thus I embraced science subjects with a new found enthusiasm. Most of my friends today had similar stories.

To be frank, it's high time girls disabuse their mind on the thought, "I lack the skills and boys would always be preferred in class". My candid advice for girls in STEM is to be serious and prepare themselves for the future because the future is theirs. But I must add, they need help because this problem has been decades in the making. Recently, I heard a story about an oil company in Nigeria that advertised for recruitment of female engineers and scientist, it was strictly for ladies, I said to myself that yes, things are changing and definitely it will change for the girls that are prepared.

4. Gender imbalance in space science and technology

In 2007 I was employed as part of a Nigerian team of Scientists and Engineers to be trained to design and build the NigeriaSat-2 and NigeriaSat-X satellites, out of 14 people employed only 2 women were selected. Similarly, for the NigComSat project in 2004, only 3 women made the team of 50 selected to be trained in China.

It is no news that women are underrepresented in STEM. In Nigeria alone (assumed to be the giant of Africa), just less than 20% of top engineers, scientist, space technology researchers and professionals are women in this 21st century. Nigeria has a very good number of higher institutions for Science, Engineering and Technology both government and private owned but it is observed that the number of female lectures in the departments are few compared to the male likewise the female to male students. With this observation, it is disheartening to note that if nothing is done to bring more girls to study STEM courses, and create opportunity, empowerment and motivation for the few women already in the field, the upcoming girls might not have mentors to look up to.

The issue of role model should be taken seriously in STEM fields in Nigeria and Africa. STEM in Nigeria has few role models meanwhile these role models are not widely seen/known because there is nothing to show forth about them. Some of the so called role models don't have a good job and as such do not live up to expectation for the girls to emulate thereby making the girls lose interest and desire in them but they rather go for the people that are been celebrated.

I could remember when we returned from NigeriaSat2 and Nigeria Sat-X mission, a great milestone in Nigeria, a thing of great joy and national honor. I was among the two ladies that went for the mission and the country did not dim it fit to celebrate us, why? I guess they government does not know the value of satellite and there were no females in the policy making that would recommend for that. Again, the day the team members were invited for presidential handshake, after the launch of the satellites, I was denied to see the then Nigerian president because I went with my baby.

Again, just in the last concluded girls programme I organized in NASRDA Abuja, as I was giving my speech, I asked (my programmes are usually interactive) the girls in attendance "who is your role models" no one mentioned anyone from science, engineering, mathematics and technology both in Nigeria and Africa. You would be amazed at the names mentioned. I was opportune to as why they don't have role models in STEM subject – story for another day.

5. Reaching out and catching them young

Following the 2019 IAC theme "Space: The power of the past; the promise of the future" you will agree with me that everything now is about technology and to make it advanced is the space technology, every other technology can stop you at a point but space technology can help you to reach the unreached especially those at the remote areas. Looking at the statistics especially in the developing countries, those living in the remote areas are mostly women. Again, considering the fact that every girl child today is a potential woman, if we can reach out to these girls at a very young age before or at secondary/high schools to make them have interest in STEM courses, if we can also be able to get these girl children to understand space technology and begin to be creators, they will be able to know the problems with respect to women, and be able to design the Apps that will help their fellow women/ladies and as such would not just become consumers where people would be dumping technologies. and this will help them to belong to the world power and equally secure their future for tomorrow. The world is a global village today

because of space technology and girls/women should not be left out.

Hence, the Women in Aerospace advocacy for awareness creation for a girl child to be involved in Science, Technology, Engineering and Mathematics (STEM). So with space technology, you can reach the world.

In the course of our advocacy in some parts of Nigeria, it is found out that the girls are still leaving in fear and exclusion in the study and participation STEM, this would have to change. So, how do we solve these problems of fear and exclusion?

First, we need to catch them young. The Women in Aerospace Nigeria (WIAN) initiative which I championed in 2012 – knowing that I couldn't do this alone – sought as many women as possible in the Science and Technology industry to visit high schools and encourage young girls to embrace STEM and most especially reach for the stars in Space Science and Technology.

The society has made the young girls susceptible to insecurity, lack of confidence and academically imbalance by upbringing and environment. For example, the Chibok girls and Dapchi girls both in Borno and Yobe states of Nigeria respectively. These made the girls to lose value on themselves, lack of confidence on both parents and teachers and even the society generally who have bought the societal ideas that they can't cope with their male counterparts in STEM fields. Meanwhile the teachers and parents are supposed to be their mentors and their source of inspiration but since they failed to get it from them, they are grip by fear of "I can't not". so the catch them young programme by WIAN has brought back the confidence in them.

The WIAN has been able to achieve this advocacy programme by creating opportunities and activities to engage the young girls in STEM so as to reinforce their potential to use space technology for national development.

6. My triumph

Finally, how have I fared in the industry so far? I've been lucky, I had a father that understood the value of the girl child education and encouraged me to challenge myself. Also, I got married to a man that appreciates the contribution a woman can bring into Science and Technology. Which tells me that we need to educate the boy child to value the girl child in Africa; to see the girl child as a partner in development and not as an object for the kitchen and the other room.

This way we can reach for the stars together and set the girl child on a path to career fulfilment especially in space science and technology.

7. Recommendations

The way forward for STEM for girls in Nigeria and Africa at large is to achieve the sustainable Development Goals (SDGs) for Space programmes:

1. United Nations (UN), African Union, National Space Agencies and other related bodies should create a network for eligible and qualified women already in the field of STEM locally and internationally.to work together for awareness creation and advocacy.
2. To advocate for STEM female professionals to be involved in decision making in Nigeria and Africa at large.
3. Space technology as a tool to generate interest and reach all young children should be encouraged by the government through the implementation of Space Museums.
4. Forums to stimulate Mentorship programmes between young girls and women currently in Space Science.

Reference

- UNESCO website

IAC-19-E1.IP.12x49312

From Spaceflight Hardware to University Student Designs: How Implementation of NASA Methodologies and Processes Ensure Project Success Irrespective of Scale

Ruth May[a]*, Christina L. Carmen, Ph.D.[b]

[a] *Mechanical and Aerospace Engineering Department, The University of Alabama in Huntsville, 301 Sparkman Drive, Huntsville, Alabama, USA, ruthie.may.flower@gmail.com*
[b] *Mechanical and Aerospace Engineering Department, The University of Alabama in Huntsville, 301 Sparkman Drive, Huntsville, Alabama, USA, christina.carmen@uah.edu*
** Corresponding Author*

Abstract

The United States (US) National Aeronautics and Space Administration (NASA) first developed the NASA Systems Engineering (SE) Handbook in 1995, with two revisions ensuing. The Handbook has been a standard used in the design and development of major aerospace systems, and has enabled government and industry to ensure the realization of high quality, durable, and reliable systems. From various spaceflight systems to university student research projects, the tools, methods, and processes identified in the Handbook have proven to be effective regardless of project scale. The present paper will describe how the NASA SE Handbook can be successfully utilized in the design and development of small-scale university projects, while also enabling engineering students to become acclimated to the methodologies employed by major aerospace engineering entities. NASA's SE Handbook defines a design process, beginning with the initiation of requirements to final product delivery and beyond, formally known as NASA's Systems Engineering Engine. The SE Engine divides the design-to-product journey into three system design processes– the systems design, product realization, and technical management processes. These three overall processes were implemented by a team of Mechanical and Aerospace Engineering (MAE) students in the design and development of a tabletop wind tunnel for Science, Technology, Engineering, and Mathematics (STEM) outreach through the University of Alabama in Huntsville (UAH). The present paper will correlate specific SE Engine processes to project success, as established by the UAH student design team. Additionally, issues and solutions will be identified, as well as lessons learned, in order to convey this knowledge to future design teams. Beginning with the requirements definition process, to functional decomposition, technical solution definition, design realization, evaluation, product transition, and the numerous technical management processes used throughout the year-long UAH design effort, the present paper will provide a guideline for small-scale project success. Additionally, it will be shown that engineering students benefit from use of the established practices detailed in the NASA SE Handbook, as it enables accelerated readiness and understanding of engineering practices prior to entering the workforce. Specific metrics assessing the learning impact on UAH CDC students will be presented.

Keywords: NASA Systems Engineering Handbook, Systems Engineering Engine, Capstone Design, Wind Tunnel

Acronyms/Abbreviations

American Society of Mechanical Engineers (ASME)
Capstone Design Class (CDC)
Commercial-Off-The-Shelf (COTS)
Concept of Operations (ConOps)
Critical Design Review (CDR)
Department of Defense (DoD)
Detailed Verification Objective (DVO)
Exploration Toolset for the Optimization of Launch and Space Systems (X-TOOLSS)
Field Programmable Analog Array (FPAA)
Field Programmable Gate Array (FPGA)
Functional Flow Block Diagram (FFBD)
Hazard and Operability Analyses (HAZOPs)
Interim Design Review (IDR)
Johnson Space Center (JSC)
Kindergarten through 12th grade (K-12)
Marshall Space Flight Center (MSFC)
Mechanical and Aerospace Engineering (MAE)
Military Standard (MIL STD)
National Advisory Committee for Aeronautics (NACA)
National Aeronautics and Space Administration (NASA)
NASA Structure Analysis (NASTRAN)
National Space Science and Technology Center (NSSTC)
North Alabama Section (NAS)
Occupational Safety and Health Administration (OSHA)
Preliminary Design Review (PDR)

Product Breakdown Structure (PBS)
Product Certification Review (PCR)
Product Readiness Review (PRR)
Project Requirements Document (PRD)
Space Launch System (SLS)
System Definition Review (SDR)
Systems Engineering (SE)
Systems Engineering & Integration (SE&I)
United Cerebral Palsy (UCP)
United States (US)
United States Dollars (USD)
United States Special Operations Command (USSOCOM)
University of Alabama in Huntsville (UAH)
University of North Carolina at Charlotte (UNCC)
Verification Method (VM)

1. Introduction

To attain successful results on an engineering design and development project, engineering entities worldwide employ SE processes. Implementing these processes helps achieve successful results by ensuring that "no stone is left unturned." Specifically, adherence to SE processes enables an engineering team to proceed through rigorous practices such that all design and development considerations, whether major or minor, are not overlooked. Basically, SE processes provide a broad "checklist" of steps to follow, which can be implemented iteratively or recursively, in order to achieve optimal project results. NASA is a prime example of a major aerospace organization that has successfully employed SE processes, and has even created an SE Handbook based upon lessons learned and evolving practices. The first version of the NASA SE Handbook was released in 1995 [1] with the intent of providing NASA personnel knowledge regarding SE processes in order to achieve ideal project outcomes. The foundation of the design process employed in the two revisions followed: the first in 2007 [2] and the second, current version, in 2016 [3].

UAH Product Realization CDC is based upon the NASA SE Handbook. The undergraduate MAE Product Realization students work in small teams (4-6 students per team) in order to design and develop a product for a real-world customer that must meet certain requirements. At the end of the two-semester class, the product is transferred to the customer for permanent use. Since 2010, when the NASA processes were first used in the class, the resulting product quality and delivery success rate has improved tremendously.

The UAH Product Realization design teams utilize a design process that is outlined within the NASA SE Handbook, formally known as the Systems Engineering (SE) Engine. The SE Engine, shown in Fig. 1, is a comprehensive outline of the design process from the initial stages of design to final product delivery. Through the implementation of seventeen steps within the SE engine, small scale projects undertaken by undergraduate senior design engineering teams, as well as large-scale NASA programs, have experienced project success. The present paper will focus on how the NASA SE Handbook and Engine were employed by UAH CDC students in the design and development of a tabletop wind tunnel. The educational impact on the UAH students, garnered as a result of working on the project and employing NASA methodologies, will be assessed.

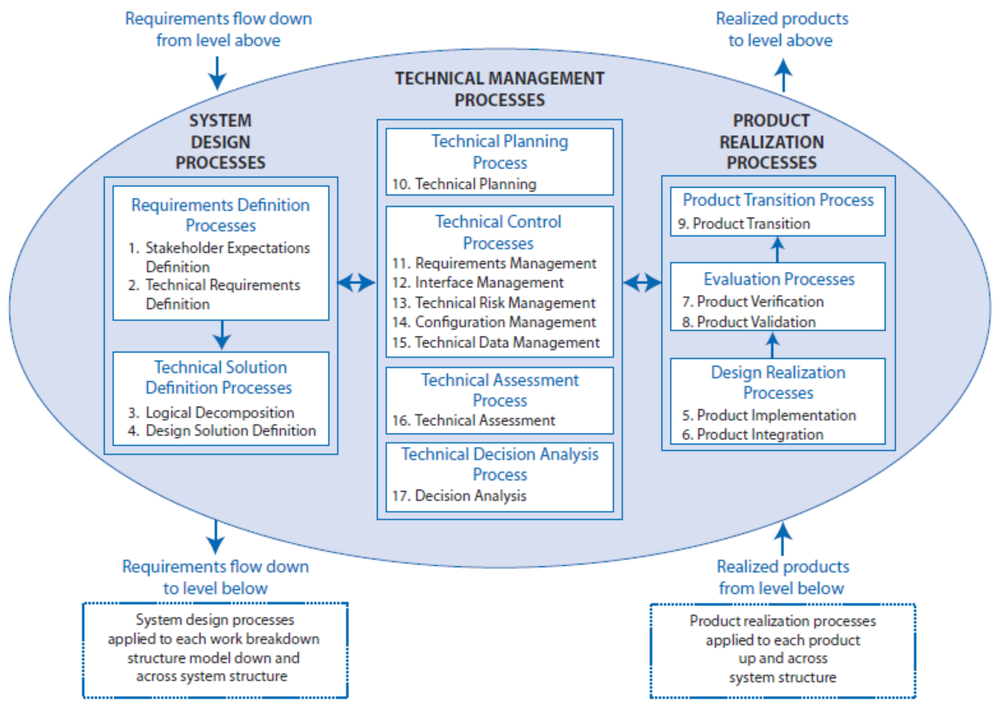


Fig. 1. The NASA SE Engine [2]

2. Background

NASA's implementation of the SE Engine for large-scale programs has been very effective, as the SE engine has inherent flexibility to meet program needs. A prime example is the SLS program. The SLS effort integrates a modified and customized approach of NASA's SE principles. Specifically, the SE&I team at NASA's MSFC focused upon the following program objectives that were to be implemented across all engineering fields [4]:

- Define the SLS system to meet requirements
- De-compose the system into hardware and software end items with assigned functionality
- Manage the technical, cost and schedule interactions of the allocated end items
- Integrate the end item designs into a certified system design
- Integrate the end item hardware and software into a flight-certified system
- Support the operation of the system.

One major focus during SLS design requirements development was implementation of extant hardware from previous programs. Additionally, emphasis was placed upon reducing and simplifying requirements and replacing derived requirements with DVOs to ensure that design criteria are met [5]. Definition of system requirements was followed by system decomposition. A pressing consideration in the design and certification of the entire system was the influence of each element on the overall system. Additionally, communication and technical management processes were, and continue to be, crucial to project success. MSFC created a matrix identifying contributors and key roles for smooth communication flow between departments. Other changes regarding the certification process were also implemented permitting NASA's SE Engine to be customized for the novel and complex challenge of creating the largest rocket to ever be launched.

While the SLS program provides an example of the effectiveness of SE practices on major NASA programs, smaller-scale designs can also benefit. An example is the utilization of the NASA SE engine by an undergraduate senior engineering design team at UNCC [6]. The UNCC team outlined multiple tasks, derived from the SE Engine, which served as success criteria for the project. These included correct and meticulous requirement definitions, requirements traceability, and documentation, which enabled the assessment of the project against stakeholder requirements for project verification and validation. The UNCC project involved the development of FPAA and FPGA boards that could be repurposed to serve multiple functions aboard spacecraft for NASA's JSC. By following NASA's SE processes, the team experienced greater success than other UNCC design teams.

UAH's integration of NASA SE processes into the Product Realization CDC has been previously detailed [7]. One example is the collaboration with MSFC engineers and NSSTC engineers whereby a Product Realization team undertook the optimization of a scaled Gemini capsule using the software programs X-TOOLSS® and NASTRAN®. The team successfully increased the capsule's factor of safety while reducing the weight and impact stress. Another MSFC based project undertaken by a UAH Product Realization team was the design of the body segments of a lunar regolith burrowing robot, called the Lunar Wormbot [8]. Throughout both projects, the student design teams implemented NASA's SE processes by conducting stakeholder assessments, performing cost, technical, and safety analyses during the system design process, among multiple other tasks. During the 2-semester design effort all 17 steps of the SE Engine were addressed via multiple presentations to engineers at MSFC. The integration of NASA's SE engine in the UAH CDC was a success and continues to be implemented in the class curriculum to the present day. NASA SE based projects provide opportunities to inculcate NASA's processes in undergraduate senior design projects, providing the opportunity for students to become highly knowledgeable with a process employed in government and industry.

3. Methodology

Since 2010, the NASA SE Handbook has been employed by UAH CDC students in the Product Realization class. Since that time, over 200 products have been designed, analysed, fabricated, tested, and delivered to a customer for long-term operational use. Over 95% of the resulting products were deemed to be functionally sound and of high enough quality to satisfy stakeholder (customers, sponsors, team advisors, and instructor) expectations - primarily due to the comprehensive design process stipulated via the NASA SE Engine.

3.1 UAH Product Realization Class

The UAH Product Realization class provides MAE students with an all-encompassing, real-world design experience. The two-semester design effort begins with students selecting a project from several options and ends with a product transferred to the customer after a rigorous operational testing period, and provision of a thorough Operations Manual and design documentation.

Project customers have included a plethora of entities including NASA, USSOC, K-12 teachers, distilleries, UCP, and the US Army, to name a few. Prior to the start of the first semester, the class instructor and customer agree upon the scope of the project to ensure that project complexity is appropriate for a 4-6 person student team to complete in two semesters. On the first day of class, ideally, a customer representative will introduce themselves and describe the requirements for the needed product. Students are able to request a 1st, 2nd, and 3rd project choice, with most students assigned to their first project choice and the remaining students assigned to their second choice. Rarely is a student assigned their 3rd choice. It has been observed that student interest in a project reflects upon the final quality of the product. Interest and enthusiasm in a two-semester long effort is important in order to ensure successful completion of the project.

Table 1 provides a broad overview of the tasks undertaken by UAH Product Realization design teams, as well as the design reviews conducted in association with the tasks.

Senior Design I-Product Realization 1st Semester	
Task	Design Review
• Requirements Definition • Research • Conceptualization • Trade Studies	SDR
• Concept Selection • CAD Drawings • Interface Diagrams • Technical Analysis • Hazard-Risk Assessment • Cost Analysis • Human Factors	PDR
• Manufacturing Ready Drawings • Additional Technical Analysis • Update PDR Tasks	CDR
Senior Design II-Product Realization 2nd Semester	
• Final Manufacturing Plans • Parts Procurement Status • Update CDR Tasks	IDR
• Manufacturing Results • Test Results • Requirements Verification Matrix • Updated Costs	PRR
• Operational Test Results • Stakeholder Assessment • Lessons Learned • Recommendations	PCR

Table 1. UAH Product Realization CDC Overview

3.2 Utilization of the NASA SE Handbook

NASA's SE Handbook has been integrated into the core curriculum of the UAH Product Realization CDC via numerous lectures that focus on the SE Engine–specifically, the System Design, Product Realization, and Technical Management Processes which are allocated into seventeen processes. The Product Realization student design teams apply the processes of the SE Engine to the design, analysis, fabrication, testing, refinement, and delivery of a resulting product. Student teams begin the process by understanding the project requirements and creating a requirements definition document, known as the PRD. Requirements definition lays the groundwork for the system's design and realization in its entirety. The process occurs when stakeholder expectations, desires, capabilities, and needs are encapsulated in *Shall* (a firm requirement), *Should* (a goal), and *Will* (a fact) statements [2]. Stakeholder expectations are defined by identifying mission objectives through communication with the mission authority, whether it is NASA, Congress, or another entity. By specifying the overarching goals of the project, operational objectives, success criteria, and design drivers can be defined. The result of this method is the establishment of top-level requirements and expectations, as well as a ConOps document. Requirements are categorized on the system or sub-system level according to the PBS. UAH Product Realization teams also develop ConOps diagrams, FFBDs, and project schedules among a multitude of other tasks. The documents and diagrams aid in ensuring that stakeholder expectations are met.

Interfaces are a major focus of the UAH Product Realization class. Teams create several interface diagrams to determine system interfaces and assess potential issues between parts. Additional tools include evaluation matrices used to evaluate concepts and requirements matrices that ensure requirements are met. These and other matrices are created based on templates and examples from the NASA SE Handbook.

Finally, NASA's technical management processes provide a structure for technical planning and project management. UAH Product Realization teams produce schedules, testing documentation, and numerous other documents in accordance with standards in the SE Handbook. The architecture of the class is designed to apply design principles and standards to small-scale engineering projects.

4. Wind Tunnel Design Process

During the 2018-2019 academic year, a UAH Product Realization CDC team designed and built a tabletop wind tunnel for STEM outreach purposes. Highlights of how the NASA SE Handbook and SE Engine were utilized will be provided, as well as examples of various design tools.

4.1 Wind Tunnel Requirements

The development of requirements encompasses Tasks #1 and #2 in the NASA SE Engine. The UAH tabletop wind tunnel design team created a PRD in which stakeholder expectations were categorized into eleven categories of requirements. Each requirement category was dissected into multiple requirements classified by requirement number, the requirement, the source of the requirement, VM, and requirement rationale. Sources of the requirements are the Customer (C), Sponsor (S), Derived (De), or Professor (P). Requirements are validated by one of the following methods: Analysis (A), Demonstration (D), Inspection (I), and/or Testing (T).

The following identifies some of the top-level requirements for the tabletop wind tunnel.

Physical Requirements:

- Each detached product section shall weigh 35 lb or less.
- The tabletop wind tunnel shall be fabricated using

parts and components available in most parts of the world.

- Specialized manufacturing of parts shall be allowed as long as an equivalent part or process is available in most parts of the world.

Functional Requirements:

- The tabletop wind tunnel shall demonstrate and measure lift of the test article.
- Test article lift shall be measured via lightweight objects added to the stinger (the mechanism that supports the test article), that can subsequently be weighed.
- The angle of attack shall be adjustable.
- Appropriate safety guards shall be installed on all chemical, mechanical, and electronic systems associated with the wind tunnel.
- Complete system and level 2 sub-system components shall be capable of assembly/disassembly with only standard hand tools (screwdrivers, wrenches, etc.) and should ideally be snap fit or latched.

The most critical requirements included the ability to demonstrate and measure lift, as well as fabricate the wind tunnel from COTS materials.

4.2 Project ConOps

The ConOps provides an overview of the product operation and is associated with Task #3 in the SE Engine – the Logical Decomposition of the Technical Solution Definition Process. ConOps incorporates stakeholder expectations and requirements in the framework of the project's operation. ConOps are important as they demonstrate how the project will fulfil stakeholder expectations.

The ConOps created by the wind tunnel team is shown in Fig. 2. The UAH design team's ConOps conveys eight phases of the wind tunnel's operation, beginning with assembly. Once the wind tunnel is assembled and the test article is mounted, lift can be observed with the airflow generated by the fan. The lift can be varied by adjusting the angle of attack and the airspeed. As the test article experiences lift, weights can be added to the weight carriage in order for the test article to descend to the constant altitude line (this line is represented as a yellow dashed line on the side of the wind tunnel.)

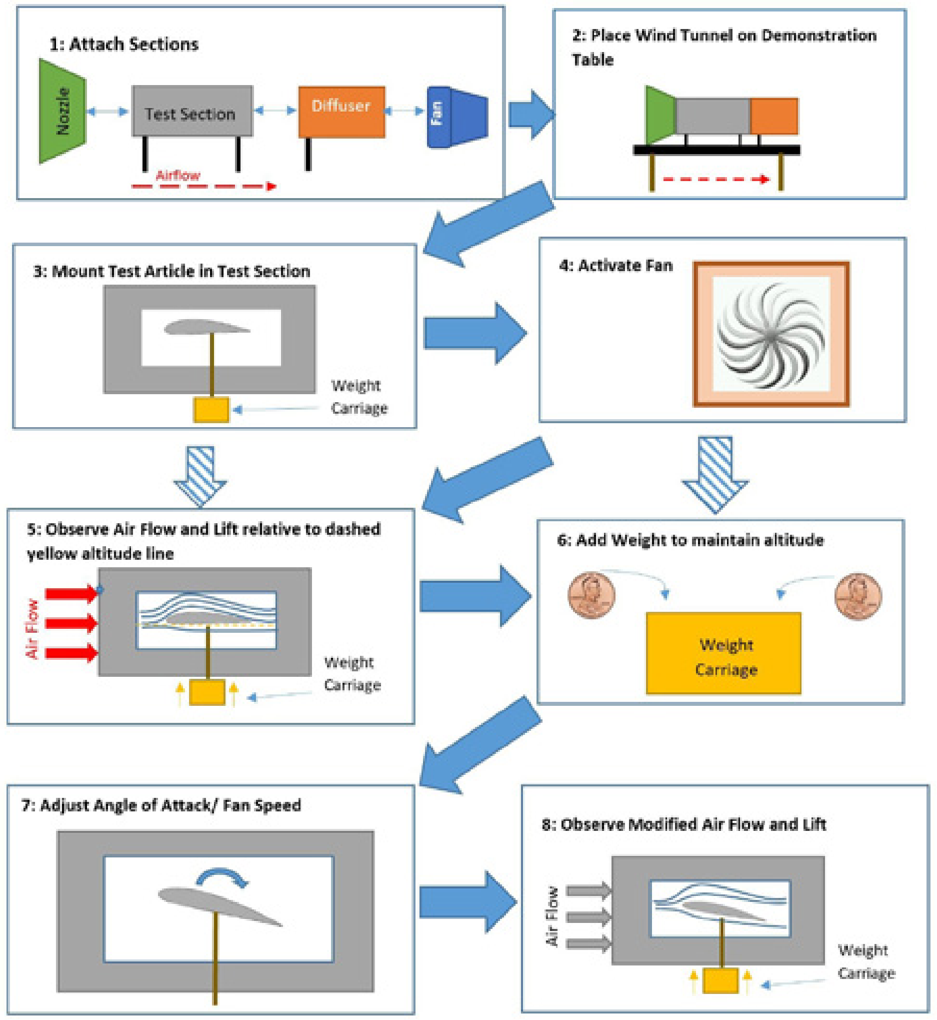


Fig. 2. ConOps for UAH tabletop wind tunnel [8]

AD ASTRA – IAC Special Issue – 2019

4.3 Functional Flow Block Diagram

An FFBD is a diagram that provides a visual depiction of the functions of a system and also is part of the Functional Decomposition represented by Task #3 of the SE Engine. Critical in functional analysis, FFBDs not only depict the overall functions of a system, but include all necessary tasks that must be completed for the system to carry out all requisite functions. Functions are decomposed into sub-functions, creating a multi-level diagram of consecutive actions necessary for the completion of a function. These diagrams are beneficial in decomposing functions into more manageable tasks and tracing a task to its related function. An FFBD is also an effective trade study tool that identifies which succession of tasks is most efficient in carrying out various functions [2].

The FFBD created by the UAH team is shown in Fig. 3. Due to space limitations, only details for Functions 1 and 4 are provided. The wind tunnel FFBD identifies the following primary functions performed over one operational cycle of the wind tunnel: preliminary setup, power up, visual component setup, testing, and shutdown. Each of the five functions are decomposed into tasks necessary for the completion of each function.

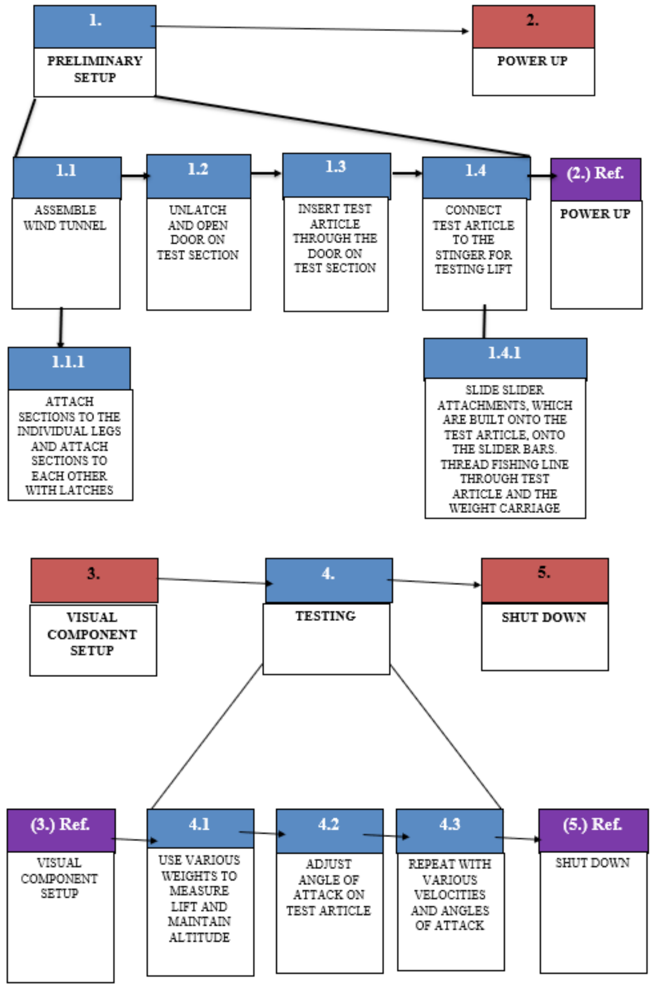


Fig. 3. FFBD for the UAH tabletop wind tunnel (note: only details for Function 1 and 4 are shown) [8]

4.4 Hazard and Risk Analysis

A hazard and risk analysis is created to evaluate potential hazards that may occur during various phases such as during fabrication or system operation. It is a necessary component of the Technical Risk Management process - specifically Task #13 in the SE Engine. The NASA SE Handbook defines a hazard as a potential state which could cause adverse effects. Risk is defined as the combination of the probability and consequences of an unfortunate event. The evaluation of both hazards and risks is crucial in preventing harmful situations.

A hazard and risk assessment can be performed through several techniques including "what if" analyses, HAZOPs, and fault tree/event tree analyses. The UAH design team created a hazard and risk assessment chart according to the MIL STD 882-B assessment standard. The chart and corresponding legend are shown in Fig. 4 which identifies the hazard, the frequency of occurrence, severity of consequence, hazard risk number, control methods to mitigate or eliminate the hazard, and subsequent results of implementing the control method.

Hazard	Frequency	Consequence	Hazard Risk Index Number	Control Method	Updated Frequency	Updated Consequence	Updated Risk Index Number
Fan blade exposure causing cuts or injury	C	III	11	Install a fan grate at least 9 inches in font of fan	E	II	15
Sharp edges	C	III	15	Apply padding at corners of base and sand all edges	D	IV	18
Manufacturing (injury from handling machines and cutting materials)	C	III	13	Use OSHA specified Machine Shop safety procedures	D	III	17
Hair entanglement in fan	E	IV	17	Longer hair should be tied back	E	IV	20
Pinch point	D	III	14	Sand edges and apply warning labels	E	IV	18
Hearing damage	D	IV	19	Enclose fan, and earplugs can be worn, if needed	D	II	10
Electrical shock	D	I	8	Power turned "on" or "off" only when plug is properly connected or disconnected from outlet	E	1	12

Frequency of Occurrence	Hazard Category			
	I	II	III	IV
	Catastrophic	Critical	Marginal	Negligible
A. Frequent	1	3	7	13
B. Probable	2	5	9	16
C. Occasional	4	6	11	18
D. Remote	8	10	14	19
E. Improbable	12	15	17	20

Hazard-Risk Index	Criterion
1-5	Unacceptable
6-9	Undesirable
10-17	Acceptable with review
18-20	Acceptable without review

Fig. 4. Hazard and Risk Assessment charts for the table top wind tunnel [8]

4.5 Project Schedules

Project schedules are essential for creating a deliverable product in the proper timeframe. NASA's work breakdown structure, which the UAH team refers to as a product development schedule, decomposes the project into a hierarchy of tasks. Milestones of the design and product realization processes are incorporated in the schedule which consists of both tasks and deadlines. In the product development schedule, activities are broken into top-level systems and sub-systems. The categorization of each activity and subsequent deadlines is helpful in tracking project progress and identifying potential barriers to meeting project deadlines.

The UAH design team created a product development schedule and team schedule. The product development schedule identified key milestones including the System Definition Review (SDR), Preliminary Design Review (PDR), and Critical Design Review (CDR) for the fall 2018 semester and the Interim Design Review (IDR), Product Readiness Review (PRR), and Product Certification Review (PCR) for the spring 2019 semester. The project development schedule is shown in Table 2.

5. Results and Discussion

The UAH tabletop wind tunnel design team successfully completed fabrication of the wind tunnel in March 2019. The use of the NASA SE handbook and SE Engine formed the foundation of the design process and enabled a successful outcome. The educational impact upon the team, as well as classmates in the Product Realization CDC, was assessed.

5.1 Completed Wind Tunnel

The wind tunnel met all but one functional requirement. The team was unable to produce all three test articles originally required. Only one airfoil was produced due to the intricate shape required to duplicate NACA airfoils. The team recommends if additional NACA test articles are desired, that professional fabrication methods be employed to exactly duplicate the shape. However, the wind tunnel met all other physical, performance, facilities, transportation, storage, durability, safety, human performance/ergonomics, personnel, training, and STEM outreach requirements. The crucial expectations for the wind tunnel to be lightweight, easily assembled and operated, and able to demonstrate lift were achieved with great success.

Responsible Manager:		Subsystem (Level 2)				Status as of:		30-Apr-19	
		(Subsystem (Level 3)				Revision Date:		30-Apr-19	
Activity		2018				2019			
		FY 2019							
		Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
1	Milestones - System	ΔSDR	ΔPDR	ΔCDR			⌂ IDR		⌂ Deliver
2	Milestones - Subsystem			DDRΔ				PRR ⌂	⌂ PCR
3	Management								
4	Quarterly Assessments								
5	System Engineering	Δ Rec' Requirements							
6	Assembly Design			ΔApproval					
7	System and Subsystem Requirements			ΔApproval					
8	Nozzle						⌂ Integrate & Test		
9	Design								
10	Fabricate								
11	Test								
12	Test Section						⌂ Integrate & Test		
13	Design								
14	Fabricate								
15	Test								
16	Defusser and Test Articles						⌂ Integrate & Test		
17	Design								
18	Fabricate Diffuser								
19	Fabricate Test Articles								
20	Test								
21	Integration and Test								
22	Plans								
23	Integrate and Test								

Key		
⌂	=	End of Task Schedule
Δ	=	Major Milestone
	=	Scheuled Period of Performance for Activity
	=	Critical Path
	=	In Progress
	=	Completed

Table 2. The tabletop wind tunnel Product Development Schedule [8]

An image of the final tabletop wind tunnel is shown in Fig. 5. Note that a NACA 0012 airfoil is positioned on the stinger within the test section. To date, the wind tunnel has been demonstrated to numerous K-12 students with excellent results – the young children have learned about airfoils, lift, nozzles, angle of attack, airspeed, and numerous other aerospace and engineering phenomena. The total budget required to produce the single wind tunnel was under 850 USD.

Fig. 5. The completed UAH designed tabletop wind tunnel [8]

5.2 Educational Impact

In order to assess the learning outcomes and educational impact on the UAH Product Realization students, a survey was administered at the start of the first semester design effort and at the end. Information was garnered with respect to the knowledge gained by utilizing the NASA SE Handbook and the affiliated methodologies, processes, and tools. The results of four questions are provided and discussed.

Fig. 6 shows the results of a survey question that queried 16 Product Realization students' knowledge of the NASA, or DoD (US), SE design process. At the start of the class, 8 students had no knowledge of SE processes, 7 students had "Very Little" or some knowledge, and 1 student replied "Fairly Well." At the end of the semester, 12 students indicated that they understood SE processes "Fairly Well" or "Very Much." These results show a significant improvement in engineering students' knowledge of these important SE processes and practices that are used in the engineering community.

A second survey question pertained to the Product Realization students' opinion regarding the benefit of familiarity with NASA (or DoD) SE processes. The results are shown in Fig. 7. While the majority of students, from the onset of the class, believed that knowledge of SE processes was important, 3 students replied "No" or "Very Little" at the start of the first semester. At the end of the first semester, all students believed that SE process familiarity was beneficial – with only 4 students replying "Somewhat."

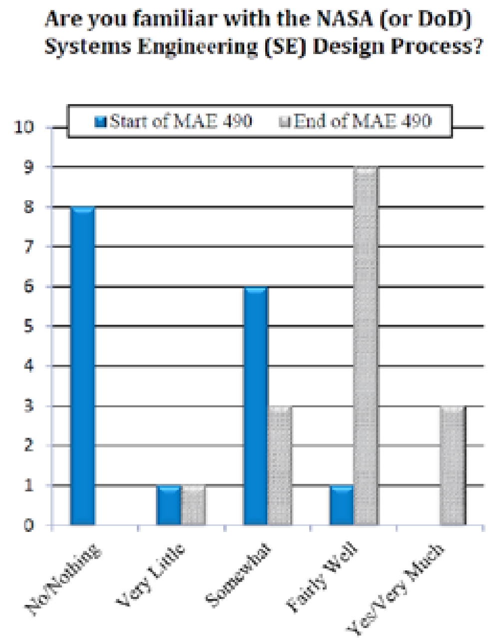


Fig. 6. UAH Product Realization survey results regarding knowledge of specific SE design processes

The next survey question regarded knowledge of evaluation matrices. The results are provided in Fig. 8 and show that half of the respondents, or 8 students, initially had no familiarity with these matrices. At the end of the semester, all students indicated that they knew what evaluation matrices were, with 11 students replying "Yes/Very Much." Evaluation matrices were emphasized within the UAH Product Realization class as being an important and critical tool in the engineering workplace, as decisions made by the design team are conveyed via the information detailed in the matrix.

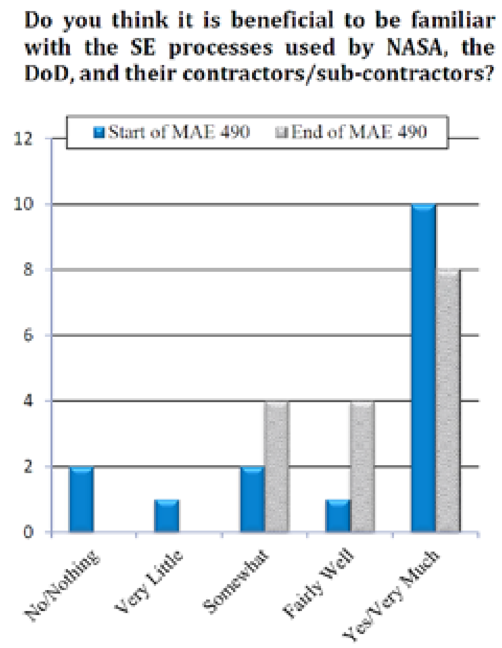


Fig. 7. UAH Product Realization survey results regarding knowledge of specific SE design processes

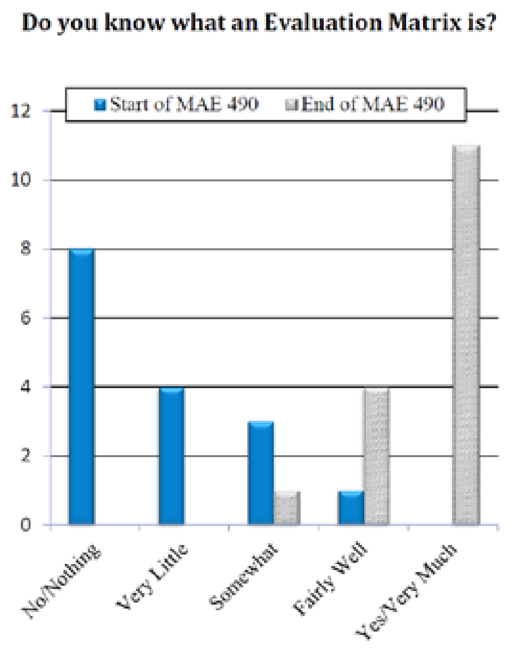


Fig. 8. UAH Product Realization survey results regarding knowledge of evaluation matrices

The final survey question inquired if the Product Realization students knew how to conduct a Hazard/Risk Assessment. As previously stated, MIL STD 882B was the required method utilized in the UAH class. As shown in Fig. 9, only 1 student initially stated “Yes/Very Much.” At the end of the semester, 10 students replied “Yes/Very Much.” Five students responded “Fairly Well” and only 1 student replied “Somewhat.”

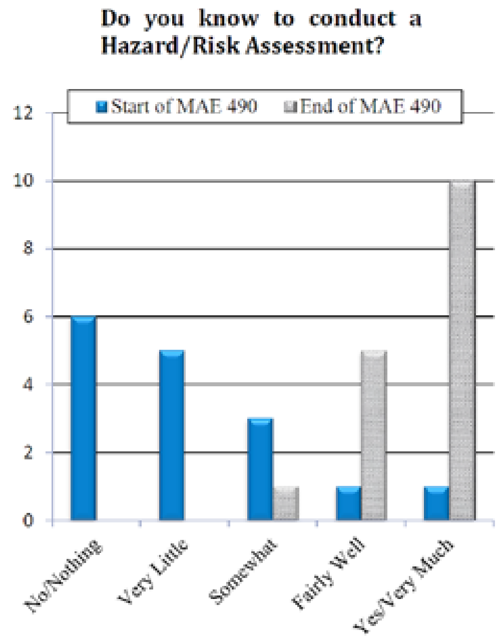


Fig. 9. UAH Product Realization survey results pertaining to Hazard/Risk Assessments

6. Conclusions

NASA first created the NASA SE Handbook in 1995. Since that time, numerous entities have utilized the Handbook as an invaluable resource. Major NASA programs, such as SLS, have consistently employed the prescribed practices and methodologies in order to achieve project success. The content and tools detailed within the Handbook ensure that design teams progress through the project life-cycle with thoroughness and rigor.

The UAH Product Realization class began implementation of the NASA SE Handbook in 2010 and the resulting product quality and durability have dramatically improved. As with all Product Realization projects, the tabletop wind tunnel effort provided engineering students with a real-world engineering design experience. From the initial understanding of stakeholder requirements to delivery of the final product, the student team obtained design experience that accelerates critical engineering readiness upon entrance into the workforce.

The educational impact upon the Product Realization students was determined via a survey conducted at the start and end of the first semester. The results show that students initially were not familiar with the NASA SE processes, including the use of tools such as evaluation matrices, and conducting hazard and risk studies.

Capstone design classes are conducted during the senior year of undergraduate engineering studies and represent the culmination of the undergraduate engineering curriculum. Employing actual SE processes used in industry provides students the opportunity to enter the workforce with relevant experience that covers a multitude of topics, thus ensuring the students can easily acclimate to the professional work environment.

Acknowledgements

The authors would like to thank the entire UAH MAE Product Realization Tabletop Wind Tunnel design team including M. Bowersox, K. Clark, C. McIntyre, A. Prathmar, and A. Singh. Additionally, the authors acknowledge the generous financial support of the UAH ASME Student Section, as well as the guidance and advice of the NAS ASME members-particularly Mr. Herb Guendel. Finally, the authors thank the UAH MAE department for their invaluable support and encouragement.

References

[1] NASA Systems Engineering Handbook, SP-610S, June 1995.

[2] NASA Systems Engineering Handbook, SP-2007-6105, Revision 1. Dec. 2007. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080008301_2008008500.pdf, (accessed 09.06.19).

[3] NASA Systems Engineering Handbook, SP-2016-6105, Revision 2. 2016.

https://www.nasa.gov/sites/default/files/atoms/files/nasa_systems_engineering_handbook_0.pdf, (accessed 09.06.19).

[4] J.J. Hutt, J. Whitehead, J. Hanson, NASA's Space Launch System: Systems Engineering Approach for Affordability and Mission Success, AIAA SPACE and Astronautics Forum and Exposition (2017) 1-11.

[5] Space Launch System Program Moving Forward with Critical Design Review, 12 May 2015, https://www.coloradospacenews.com/space-launch-system-program-moving-forward-with-critical-design-review/, (accessed 14.05.19).

[6] J. Conrad, NASA Senior Design: Systems Engineering and Reusable Avionics, American Society for Engineering Education (2010) 1-15.

[7] C.L. Carmen, Integration of a NASA ESMD Faculty Fellowship Project within an Undergraduate Engineering Capstone Design Class," Acta Astronautica (2012), 141-153.

[8] J.A. Johnson, B.D. Sanders, C.L. Carmen, Design and Development of a Ground Based Robotic Tunneling Worm for Operation in Harsh Environments, IAC-11. A5.3.-B3.6.9, 62nd International Astronautical Congress Proceedings, Cape Town, ZA, 2011, 3-7 October.

[9] M. Bowersox, C. McIntyre, P. Anantwar, K. Clark, A. Singh, R. May, Final Report: Design of a Tabletop Wind Tunnel, UAH MAE 491 Product Realization, 24 April 2019.

IAC-19,E1,IP,18,x50349

The Latinamerican space workforce development and the contribution of the Andean Road Countries for Science and Technology (ARCST) to the Region

Marco Antonio Cabero Z.[a]*, Gerson Cuba[b], Michael Gonzales[c], Luan Henrique[c], Jose Angel Aponte[c], Elyka Abello[c], Marcelo F. Condori M.[c], Magdalena Gonzalez, Antero Castro Nieto[c], Gabriel Jaimes[c], David Lopez Rios[g], Zhang Xiaoxin[e], Raimundo Gonzalez Aninat[h] and Wang Xinsheng[f]

[a] *International School of Beihang University, Beijing, China, 100191*
[b] *School of Electronics, Universidad Nacional de San Agustin de Arequipa, Peru*
[c] *Regional Centre for Space Technology Applications, International School of Beihang University, Beijing, China, 100191*
[d] *School of Information and Communication, Beihang University, Beijing, China 100191*
[e] *School of Communication, Communication University of China, Beijing, 100024*
[f] *School of Astronautics, Beihang University, Beijing, China, 100191*
[g] *School of public policy and management (SPPM), Tsinghua University*
[h] *Embajador en Misión Especial y académico de la Universidad De Chile y de FLACSO*
marco.cabero@buaa.edu.cn
* Corresponding Author

Abstract

Curiosity and exploration are vital to the human spirit and accepting the challenge of going deeper into space will invite the citizens of the Latinamerican countries today and the generations of tomorrow to join the Andean Road Countries for Science and Technology (ARCST) on this exciting journey. The first step in embarking on a long and challenging journey involves laying solid groundwork for a successful endeavor. For that, the ARCST serves as the first Latinamerican organization focused on tackling the challenges, opportunities and innovative approaches to developing the current and future global space workforce. Here, we report the results of the first workshop organized by the ARCST where several students and young professionals immersed on the Space Technology gathered to discuss about the challenges on opportunities in the space field faced by the Latin-American region. Our understanding about its current status will pave the way for the future cooperation and the development of the space workforce in Latinamerica.

Keywords: Andean Road, Latinamerica, space workforce, small satellite technology

1. Introduction

Humanity's interest in the heavens has been enduring that has led to explore the unknown, discover new worlds, push the boundaries of our scientific and technical limits. The intangible desire to explore and challenge the boundaries of what we know and where we have been has provided benefits to our society for centuries1. Through addressing the challenges related to human space development we expand technology, create new industries, and help to foster a peaceful connection with other nations.

On July 30th of 2018, the kick-off of the project "Andean Road Countries for Science and Technology - ARCST" was carried out at Beihang University in Beijing, China. The event had the participation of official representatives of five Latinamerican countries: Bolivia, Colombia, Peru, Mexico, and Venezuela as well as University professors, and experts from different fields of ARCST.

Fig.1. Official photo of the event with representatives of the embassies, Professors of Beihang University and members of ARCST at the kick-off meeting of the Organization.

During the kickoff meeting several reasons why Latinamerica needs to improve its Science and Technology (S&T) capabilities, how we could support the development of projects and solutions using the expertise of the Latinamerican members of the ARCST.

The idea is to contribute and promote the "Technology Transfer" among Latinamerican researchers and professionals. The Andean Road is highly committed with the improvement of Latinamerican people's lives by supporting Science, Technology, Education and professional growth.

It is important to point out that the name "Andean Road" was inspired from the Inca Trails Empire, a road network that connected Latinamerica centuries ago. Although "Andean" is the original name, the ARCST project plans not only to integrate people from the mountain region but from all Latinamerica. This was just the beginning of the dream, welcome dear readers, investors, institutions and companies to be supportive of this initiative.

Fig.2.Group photo of the participants in the first workshop organized by the Andean Road in 2018.

2. Developing the space workforce

In order to establish a solid structure and fulfill our mission and vision, we held a workshop in coordination of Beihang University. This workshop celebrated the 30th and 31st of October 2018, gathered more than 60 representatives from different Latinamerican countries that discussed the main problems related to the space field and its possible solutions. The workshop also counted with the presence of various authorities from Beihang University as well as industry representatives. The event served to strengthen the relation between professionals of the space related field, the industry and the academia from different countries of Latinamerica residing in China.

Fig.3. Magdalena Gonzalez Liaison officer of Chile during the small satellite workshop in 2018

3. The space-related problematic

During the first day of the workshop, the delegates and the members of ARCST identified key problematics that affect the region and could be solved with satellite applications. Below they are shown in more detail.

3.2 Natural disaster response

Natural disasters are present everywhere and South America is not the exception. Most attendants explained serious experiences in their countries about natural disasters. Nowadays, there are plenty of resources in order to analyze these disastrous events. Even though, sometimes the actions taken are not as effective as expected. In fact, when some disaster events occur in the Andean region, the response is not immediate. So, there was a consensus that better well prepared and trained human resources are required to process and analyze the situation faster and more efficiently.

3.2 Lack of Research in Human Resources

There was plenty of discussion about the necessity of training professional analysts. Nowadays, there are plenty of available free resources which might be used by analysts. Even though, the capabilities in specific areas are still limited. For example, there is a software for processing certain kinds of satellite images, but the staff does not know how to use the tool properly or does not take all advantages of a software tool. In this sense, it was established that a higher level of development in the education system is required. As a result, a bridge with China would be established through universities in order to promote and strengthen training and knowledge acquisition.

Fig.4. Luan Henrique Liaison officer of Brazil expressing his point of view during the small satellite workshop in 2018.

3.3 Vehicle tracking

Smuggling is a high economic problematic for several countries of the region, so participants mentioned the importance of implementing satellite technology in order to improve the systems for tracking vehicles containers in order to prevent it.

3.4 Land Identification for Agricultural Purposes

One of the main areas of research and improvement for remote sensing satellites is focused in agriculture. China has widely launched and developed several satellites for this purpose. As a result, several participants discussed about this problematic in their countries. The two main issues related are deforestation and identification of illegal crops.

Deforestation has affected widely countries such as Brazil, Peru and Bolivia. The Amazonas is considered as one of the most important oxygen reserves in the world, but unfortunately, this natural resource has been depredated especially during the last years. So, it is of high importance to improve the remote sensing systems in order to monitor deforestation. Several ideas were proposed even to adopt real time systems for this purpose.

Another important application is that it can be implemented for the immediate identification of illegal crops. Drug trafficking is a big problem present in countries such as Bolivia, Colombia, Peru and Brazil. Therefore, it is necessary to implement systems able of monitoring illegal crops.

Fig.5. Roberto Guachi from Ecuador co-founder of the Andean Road participating on the small satellite workshop 2018.

3.5 Identification of Water Resources and Prevention of Water Scarcity

Nowadays, LANDSAT 8 images processing applied in order to monitor the status of rivers, ponds, lakes and mountains. Further and deeply analysis on ice movement and melting can be achieved by processing SENTINEL optical and microwave images. SENTINEL images are pretended to be used because these are high resolution images and are free.

Some difficulties come by two applied processes. The first one is related with downloading; SENTINEL images are really heavy (12 GBytes in average) especially microwave images. Processing and analysis of images also requires expertise and experience in order to achieve good results. In this sense, these questions can be analyzed for this purpose:

Do you have expertise in using SNAP software? If so, is it possible to acquire some training and guidance about useful procedures for processing and analysis?

Is there any other mechanism in order to process and analyze SENTINEL or any other microwave remote sensing images? If so, is it possible you could mention the sources (preferably free resources)?

Which requirements might be necessary for designing a microwave remote sensing software? Is it feasible to achieve this goal?

Which strategies could be applied to implement a system of clusters or high-speed servers which could help to download and process satellite images?

SENTINEL images are also applied for deforestation monitoring. The reason of these consults is related with the Bolivian remote sensing problem The government through the Bolivian Space Agency has a long-term goal of launching a remote sensing satellite. Even though, the professional staff in the field of remote sensing is not yet well trained to take full advantage of today's free available resources. In this scenario, the idea is to promote maximum utilization of free resources, so that when a new remote sensing satellite is launched in Bolivia, there will be enough capacity of professional staff to maximize the profit and the high investment of the project will be justified.

Fig.6. Michael Gonzales from Bolivia co-founder of the Andean Road participating on the small satellite workshop 2018.

3.6 Low Capacity in Telecommunications Download Throughput

This topic was discussed considering the situation of Bolivia. The first satellite was successfully launched some years ago. Even though some technical issues did not enable the maximum performance of this satellite,the project meant a good investment for the country. Right now, higher capacity is required, so there is a medium-term project for launching a second telecommunications satellite. In this sense, the main idea was to obtain guidance and orientation in well- known strategies to balance the traffic between the two satellites once both of them are in operational status.

Fig.7. Gerson Cuba from Peru co-founder of the Andean Road participating on the small satellite workshop 2018.

4. The space workforce in action, the plausible solutions

During the second day of the workshop, previous problems were discussed. Some important conclusions were established about certain problems. Before establishing possible final solutions, it was remarked by the attendants that solutions should have taken into account the use of small satellite (micro or nano-satellites).

Fig.8. Marco A. Cabero, President of the Andean Road participating on the small satellite workshop 2018.

4.1 Natural disaster response

After considerable discussions among participants, it was concluded that the best solution for this problematic comes by the wide use of meteorological satellites. As a result, the small satellites would have some limitation in time usage because continuous monitoring for long time is required for disaster monitoring. Even though, some positive comments were discussed in sense that small satellites would accomplish some benefit in post disaster response. Even though, an appropriate contingency plan might be highly required for this purpose.

Fig.9. Group photo of the participants of the small satellite Workshop during our technical visit to local satellite companies.

4.2 Lack of Research about Space Technology

In this point, participants agreed that there is a need to develop the Latinamerica technological capabilities in other to bolster research and academic activities related to the Space Science. And integrate different regions through the same weather or agricultural problematic in order to propose real time solutions that benefit the region.

4.3Vehicle tracking

The tracking of vehicle containers requires full time service monitoring during long periods of time. In this sense some limitations of using small satellites were remarked. Even though, it was established that if a well- designed engineering is implemented, then small satellites would help on this issue taking into consideration the periodicity in which the small satellites would be launched into the space every year.

Besides the discussion and analysis, several dissertations were collected about current status of the satellite technologies in different countries. Below, a summary of four countries is presented.

For the land Identification for agricultural purposes, the identification of Water Resources and Prevention of Water Scarcity, due to time constraints it was not possible to discuss possible solution, although the topics carry a big importance for the feature of the Latinamerican region.

About the Low Capacity in Telecommunications

Download Throughput, we consider that concerns exclusively to the already installed based and technology. ARCST considers to provide advice for policies related to the future technology that could be acquired or developed in the region.

5. The current status and the space related challenges in Latinamerican

As part of the workshop, ARCST offered the opportunity to the delegates of the workshop to provide news to the participants about the evolution of the Space Technology applications in their countries. This is the result:

Fig.10. The Senior Advisor of the Andean Road Prof. Wang Xinsheng in company of the Ambassador of El Salvador Eddie Martinez in the Popular Republic of China.

5.1 Brazil

The Brazilian history of satellite development began in 1993, when the first Brazilian satellite was launched, the SCD-1 with the project, construction and operation carried out by INPE (National Institute of Space Research), designed to collect environment data.

Since then Brazil has been developing and launching a couple of new satellites, one mission which worth a citation is the CBERS program carried out by the Brazil-China partnership, through the institutions INPE and China Academy of Space Technology (CAST), fundamentally to monitor deforestation, agricultural areas and urban development. The CBERS Program was one of the responsible for the popularization of remote sensing in the country.

Concerning the educational area, in recent years Brazil, courses focused on the space field have been implemented in several universities. There has been showing results in the field of microsatellite development, as example the nanosatellites SERPENS 1, AESP 14, NanoSatC-Br, ITASat, all developed in partnership between universities, government institutes and companies, all with participation of undergraduate students.

Fig.11. Members of the Andean Road in company of the representatives of the Brazilian Space Agency.

5.2 Venezuela

On October 29th 2018, Venezuela celebrated the 10th anniversary of its first satellite: VENESAT-1. Venezuela's second satellite, VRSS-1, is a remote sensing satellite. It was launched on September 2012 and now it has six (6) years successfully in orbit; already one more year beyond its designed lifetime and it is expected to last at least one more year. The third satellite, also a remote sensing, was launched on October 2017. It has now one year successfully in orbit. On all three programs, the satellites were delivered together with the knowledge transfer. For the VENESAT-1 program, the Popular Republic of China gave training for 90 professionals;

for the VRSS-1, 54 persons were trained and for VRSS-2, also around 60 person participated in the project.

As for ground segment, Venezuela has two places for ground stations. The first one is in Guarico, at the center of the country; here is the ground station for the control of VENESAT-1, VRSS-1 and VRSS-2, and the teleport. The second place is Luepa, it has a ground station backup of VENESAT-1.

Other than space segment and ground segment, there is also the Venezuelan Design and Assembly project: a center for design, assembly and test small satellites, up to 1000 kg; a project that is still under development.

Personnel training is also a very important part of Venezuelan Space program; the first training programs were done by the Popular Republic of China to Venezuelan professionals, but now there are Venezuelan people giving training programs to Venezuelan people. The Bolivarian Agency for Space Activities (ABAE) has training programs on GNSS, Geomatics and satellites control and operation, among others.

Fig.12. Members of the Andean Road in company of the representative of the Venezuelan Space Agency.

5.3 Peru

Peru is located in the west side of south America. Having three main regions: coast, highland and jungle. Due to the diversity of the geography the country has several topics to be solved. Such as illegal mining, deforestation, smuggling, etc. In that sense the government decided to buy and finally lunch an observation satellite on September 2016. The satellite PERUSAT-1 is currently operated by the national space agency CONIDA and it is aimed to take images with suitable resolution in order to mitigate the national problems mentioned earlier.

To date, on the other hand, have been released many academic projects related to the satellite technology. In 2013 was lunched the first nanosatellite PUCPSAT-1, promoted by Catholic university of Peru. In 2014 was lunched the nanosatellite CHASQUI -1, project promoted the National university of engineering (UNI), the same year was lunched UAPSAT-1 promoted by Alas Peruanas University. All these projects were nongovernmental projects but rather private initiative, however the development of these were quite important to generate human resources on this field.

"Thanks to this workshop all my country mates are expected to share the different issues in the region in order to support each other on the mitigation of these ones". As expressed by one participant of the Workshop from Peru.

Fig.13. Members of the Andean Road in company of the representative of the Peruvian Space Agency.

5.4 Bolivia

From our knowledge, it can be considered that Bolivia has not developed considerable expertise in Space Technologies. As a first experience scenario can be mentioned the "Tupac Katari Satellite" project, where for instance, on August of 2010, with the issuance of supreme decree 0599, the Bolivian Spatial Agency (ABE) becomes a strategic national public company with its own legal personality oriented with telecommunications scopes in national operators.

On December of 2013, the Tupac Katari satellite is put into orbit by the Xichang Satellite Launch Center in China, for which 74 Bolivians are scholarships for the management of it. Careers Space Sciences and Technology are not formally considered as professional careers by Universities System in Bolivia. Nevertheless, specialization from electronic, telecommunications, mechatronics, electromechanics, electric, informatics or physics bachelor can proceed from actual institutions and study programs.

From this situation Bolivia already achieved constructive experiences, since TKSat -1 is a communications Satellite, National Telecommunications Operators established co-operative projects with specific satellite services as national television broadcasting and internet. The Bolivian operator Entel worked on development of "telecentres" national project, which was divided in two stages, the implementation of more than 1600 telecentres focused in rural area lead to a second stage, where technical capabilities at transmission segment, topographic diversity of selected beneficiary areas, key performance indicators, and frequency plan requirements, where scope of evaluation for further engineering applications of Direct to Home (DTH) service were performed.

Prospective of Space technology application in Bolivia is based with future scopes of Bolivian Space Agency, telecommunications segment, academia ventures, private and public entities, since the implementation of remote sensing, GIS applications,

Small Satellites technology, GNSS labs, processing of data, optimization of processes, and integral technology development are part of actual and future Engineer's responsibility, suitable environment for such an important scope of formal support for professional academia, insertion in research, and capability building. Lack of technology features in this segment, should be considered as a good chance in order to reach large scale the space technology projects.

It is true that academy in Space Sciences needs formal processes of evaluation and implementation for development in Bolivia. Continuous adjusting, paradigm break, and innovation must be transcended in the formation of this apparently unknown field. Gradual evolution and evident progress will be produced by reference building guidelines.

Fig.14. Members of the Andean Road in company of the representative of the Bolivian Space Agency.

6. Conclusions

The Latinamerican space workforce gathered for the first time at Beihang University to discuss about the space related problematics in the region, the common problems, the challenges faced by different countries and plausible strategies to minimize the problems. As a general agreement, working together to solve similar problematics was accepted as one solution due to the lack of funds, or specific space programs. Fostering the Latinamerican talent seems to be a fundamental task in order to develop this space workforce. Under this scenario, the Andean Road aims to integrate different actors in this field, including spaces agencies, universities, research institutions, schools and society in general.

Latinamerica limitations' together with the meteorological and social problems particular to the region deserve a different perspective for appropriate solutions regarding the space related activities. Developing common strategies, synergy of actors involved, the promotion and cooperation among countries and professionals could certainly benefit the development of its own space workforce.

Note

At the moment of the workshop, several co-authors had one affiliation while being in China, at the moment, several of them have decided to maintain their affiliation at that time while others decided to change it.

Acknowledgement

ARCST acknowledges the support of the Professors of Beihang University and the School of Astronautics for helping to host the workshop. We extend our regards to all the Latinamerican professionals that participated in the workshop and offered such valuable suggestions to develop the space workforce in our region.

We are grateful for the fruitful two days of workshop and for the time of the embassy and space agencies representatives for their time and advice.

References

[1] Bruno Sarli, Marco Cabero, Alejandro Lopez, Josue Cardoso, Diego Jimenez, et al.. SOUTH AMERICAN SPACE ERA. 66th International Astronautical Congress - IAC 2015, Oct 2015, Jerusalem, Israel. pp.11, 2015. <hal-01216788> Available from: https://www.researchgate.net/publication/319664334_South_American_Space_Era [accessed Jun 20 2019].

IAC-19-E7.IP.19,x50215

Partial Ownership for Outer Space Economy

Erwan Beauvois[a]*, Guillaume Thirion[b]

[a] *International Master SEEDS, Politecnico di Torino, Torino, Italy, beauvois.erwan@gmail.com*
[b] *International Master SEEDS, ISAE-Supaéro, Toulouse, France, guillaume.thirion@isae-alumni.net*
* Corresponding Author

Abstract

The most widely adopted agreement on space law, the Outer Space Treaty (OST) (1967), actively promotes international partnerships and peaceful uses of outer space. It also forbids any claims of sovereignty or private property on celestial bodies; however, nothing is explicitly written about the use of resources that can be found there. Other texts, like the Moon Agreement (1979), attempted to correct this, but only 17 nations signed this agreement, because it also contains obligations that remove all incentives for the private industry to participate in the exploitation of outer space resources, such as the obligation to disclose all discoveries and share the benefits between all state parties. Today, most missions are scientific, so there is no need to compete for using space resources. If tomorrow society wants to incentivize participation, and leverage the available funds, from the private sector to explore and exploit outer space, an allocation mechanism that allows to dispute the use of resources needs to be set up. On Earth, this is achieved by the private property system and commercial competition. However, private property is not allowed by the OST, because it has a right of exclusion, and everyone shall be free to use space resources if it does not interfere with activities of other nations. An exclusivity of use for the first nation to exploit a given resource is not desired either and is precisely why the OST was established in the first place. In full compliance with the OST, this paper introduces the concept of Partial Ownership of Outer Space Resources (POOSR). This system allows to compete for the use of resources, without granting monopoly, as it always keeps the competition for ownership open. It is based on the introduction of a Harberger tax and a Partial Ownership system, that allows to expose commonly-owned resources (such as outer space asteroids, or planetary surface areas) to the efficiency of allocation provided by market dynamics, while preserving the incentives for investment to the current owners and preventing resource locking. This paper shows how such system would foster investments from private entities, as well as how it would benefit to all the international entities or nations participating to it. The synergy between such system, international regulations, and national laws, to establish a regulation for space mining and other outer space activities is also discussed.

Keywords: Space Mining, Law, Governance, Economics, Ethics, Partial Ownership.

1. Governance

Exploring new planetary bodies and exploiting their resources to set up a sustainable space infrastructure is a medium-term objective for all major space-faring nations, but how can we organize to get there? How can international collaboration be fostered to decide common policies, tackle common issues, preserve sovereignty of the nations, and stimulate economic growth of all the participants?

This section introduces current space agreements and proposes a governance structure for international collaboration on large scale projects like Asteroid Mining, Moon exploration, and Mars settlement. A decision-making process that is compatible with specialized interests is introduced, and it is discussed the role of private companies, as well as some ethical considerations.

1.1 Current situation

Conquering the new frontier by returning to the Moon, sending humans to Mars, and unlocking the Asteroids resources is a unique opportunity to capitalize on our human experience and think about how we could organize space societies, and offer a fresh start to a new branch of civilization, by fostering international collaborations and address the legal challenges faced by space mining today.

That being said, the next humans returning to the Moon, and the first who will set foot on Asteroids and on Mars will not be founding a colony or establishing a society but conducting a space exploration mission. Few astronauts will get there at first, perhaps only for short stay missions. Then regular manned missions will be conducted, from multiple agencies, and perhaps even by private companies. It does anyway sound a bit far-fetched to talk about a "civilization" when we are actually talking about only a few people at first.

The initial "flag" missions will probably be conducted without much concerns about an outer space governance structure. But as humankind progresses towards its space exploration endeavours, we observe that nations and space agencies push toward collaboration over competition. Big projects like the ISS, Hubble Space Telescope, or rovers, are conducted as an international effort, and alliances like the ISECG (International Space Exploration Coordination Group) are formed to establish common goals and a Global Exploration Roadmap (GER) [1].

The Outer Space Treaty [2], established in 1967, has been ratified by 108 countries and signed by 23 more. It is an agreement between the major space-faring nations to establish a baseline legal framework regulating space exploration. It actively promotes international partnerships, peaceful use of space, and introduces several concepts that are important to note before thinking about a governance structure for outer space resources:

- "There shall be free access to all areas of celestial bodies" Art. I.
- "Outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty" Art. II.
- "State Parties to the Treaty shall bear international responsibility for national activities in outer space, including the Moon and other celestial bodies, whether such activities are carried on by governmental agencies or by non-governmental entities" Art. VI.
- A nation shall not have "potentially harmful interference with activities [of other nations] in the peaceful exploration and use of outer space" Art. IX.

In other words, there should be no private property in space, because it would introduce a right to exclude others, and to prevent them from using a property. It would not comply with the principles of the OST, as every land shall remain "the province of all mankind" and there shall be "free use", if it doesn't interfere with activities of other nations. Also, nations are responsible for their private companies and citizens actions in space. This prohibition of private property is subject to interpretation and several national laws, like in the U.S.A. and Luxembourg, are materializing a different interpretation and are essentially granting their companies a right to claim private property in space. In 2015, the US Commercial Space Launch Competitiveness Act (HR 2262) of the Obama Administration states in Title IV – "Space Resource Exploration and Utilization" that the USA must facilitate the recovery of resources coming from space for all its citizens. This resources appropriation, even if facilitated and even sometimes funded by the American government, does not impose American sovereignty on the celestial bodies according to the Act. In 2017, Luxembourg took inspiration from the USA and passed a space law stating in its first article that space resources are allowed for appropriation if the operator is settled in the country and has an approval of the Ministry in charge of economy and space exploration. National legislations are a good strategy to offer guarantees for private investments, but don't offer a satisfactory conflict resolving mechanism, and will probably cause problems in the future when multiple nations will be interested by the same resources (certain orbits, asteroids, or areas of the Moon and Mars certainly have special value).

A dynamic where nations play with their regulatory framework to attract private space companies on their land is taking place. A trade-off must be performed by every nation, as more flexible laws will attract more companies, but also increase the risk of those companies inadvertently crossing some forbidden lines (pollution, generation of debris, contamination, ...), for which the nation will be held responsible for.

Indeed, this increase in national legislations asks the question of whether the future of space law resides in international right or if it will be driven by national laws, which can only be enforced in state's territorial jurisdiction. The question of the use of outer space resources needs to be answered, and an allocation mechanism and authority needs to be internationally agreed in order to prevent conflicts between nations.

1.2 Analogous situations

To justify outer space resources utilization, states usually take inspiration from the United Nations Convention on the Law of the Sea (UNCLOS) which inspired the OST. Article 136 states that "The Area and its resources are the common heritage of mankind" where "The Area" refers to "the sea-bed and ocean floor and subsoil thereof, beyond the limits of national jurisdiction". Then, the international seas use is based on the freedom principle notably of circulation or fishing with only limitations due to the international law with fishing quotas for example. However, this case of the UNCLOS can find its opposite in the specific case of Antarctica usage which is a transposition on Earth of some principles of the OST. The Protocol on Environmental Protection to the Antarctic Treaty (1991) provides for comprehensive protection of Antarctica, the last great wilderness on earth. The countries which ratified the Protocol commit to comprehensively protect the environment of the Antarctic region and dependent and associated ecosystems. Among other, if Antarctica is designed as a "natural reserve, devoted to peace and science", all mining activities are banned indefinitely stating in Article 7 "Any activity relating to mineral resources, other than scientific research, shall be prohibited". Contrary to a common misconception, there is no time limit on the mining ban and there are strict rules for modifying the ban.

Until 2048, the unanimous agreement of all countries engaged in the management and governance of this territory would be required to remove the mining ban. Later that time, any country may request to review this ban in a conference in which three quarters of the countries which adopted the Protocol in 1991 adopt the modification and three quarters of the countries implement it (of which, all signatories from 1991) to enter the modification into

AD ASTRA – IAC Special Issue – 2019

force. In addition, any amendment removing the mining ban can only occur if a legal regime for controlling mining is in force and if the sovereign interests of countries under Article IV of the Antarctic Treaty were safeguarded. Unless an amendment is adopted in the manner set out above, the mining ban will remain in force indefinitely. Taking inspiration from Antarctica, a collaboration between nations to establish an enforceable legal framework to govern the use of outer space resources in a responsible way can be established.

Whether it is on the legal or engineering side of things, there is value in collaborating, and it is ultimately more beneficial for every nation to do so. Countries who were denied entry in the ISS program like China greatly suffer from this rejection, as it impairs a bigger financial charge upon them to benefit from the same technological advancements and scientific knowledge. A proposition for governance and economic structure for outer space exploration and exploitation that is both inclusive, in line with the existing laws, guarantees proportional returns on investments, and lays the foundations for a future space-based society, is detailed in the following paragraphs.

1.3 Outer Space Alliance

On Earth, a new intergovernmental organization is founded. For this document, we will call such an organization the Outer Space Alliance (OSA). Following the model of the United Nations (UN), every country is free to join: it is "open to all peace-loving States that accept the obligations contained in the Charter and, in the judgment of the Organization, are able to carry out these obligations" [3]. While very similar, it will be explained later why it is important that such an organization remains independent from the UN and can't be created as a specialized agency within the UN.

Much like the governance model of the European Space Agency (ESA), all member states are given an equal amount of voting power, regardless of their financial contribution. Countries with higher financial participation are compensated by being awarded more contracts from the OSA. This concept is called geographical return and guarantees a proportional return on investment to every participant: if the U.S.A. are funding 35% of the OSA, 35% of the awarded contracts value will go to the American industry. There might be a required minimum contribution and mandatory projects so only countries that plan to have a participation in space exploration activities shall join the OSA.

1.4 Radical Democracy

As mentioned, member states are free to modify their own national laws to favour certain kind of activities in space (think of Luxembourg and the U.S.A. regarding Space Mining). Certain countries might have a leading industry in the sector of transportation, while others are more performing in human spaceflight, life support systems, in-situ resource utilization (ISRU), etc. Therefore, all member states will have stronger preferences and stronger interests in certain decisions, while they may not care as much about other subjects. A traditional voting system (1-person 1 vote, 1P1V) does not allow to capture different degrees of caring, and this is a problem for dealing with a large international project like space exploration that envelops such a big variety of different topics. It could be interesting to make use of quadratic voting, as introduced in [4] and discussed in-depth by Glen Weyl in his Radical Markets book [5]. Under such a system, every member state would be given a certain amount of Voice Credits, for free, every year. When a new issue arises, and a decision must be taken, member states can purchase votes with their Voice Credits, with the cost of an additional vote increasing quadratically with the number of already purchased votes, hence the name of quadratic voting (cost = votes2), or radical democracy (votes = √cost). This scaling speed is not arbitrary and while out of topic for this paper, it is explained in depth in the book why quadratic scaling is the just price to pay for imposing your preferences upon others. Let's provide some examples to understand how such a system would work:

- A decision regarding space transportation must be taken. With its strong private launchers industry, the U.S. is caring a lot about this issue and is buying 5 votes at the cost of 25 Voice Credits. On the other hand, the Netherlands has no launcher program and other priorities, so they save their Voice Credits for later, buying 1 vote at the cost of 1 Voice Credit.
- Being a major reference in building human-rated space habitats, Italy cares a lot about Human Spaceflight and casts 3 votes on each issue, costing 9 Voice Credits each time. While Japan is more focused on robotic exploration and only uses 1 vote costing 1 Voice Credit on each issue. Japan has a larger remaining budget of Voice Credits and when decisions impacting robotic exploration will arise, they will be able to have a bigger impact.

As mentioned in Radical Markets [5] (*this paragraph is almost entirely quoted*), this voting system still has flaws: it is not resistant to collusion, vote-buying, or fraud. But so are 1 person 1 vote systems. A separate law enforcement mechanism needs to be in place. Quadratic Voting, however, deals better with minorities and specialized interests. Small groups may still lose to the majority, but they will not lose to a majority with weak preferences. Majorities will prevail over minorities, as they should, when the intensities of everyone's preferences are similar. But when minorities have sufficiently intense interests, they can protect their interests from majority domination.

1.5 Private Companies

Many space enthusiasts believe that private companies will lead the way in space exploration. Under such assumptions, one could argue that private companies should be able to join the OSA on the same basis as nations can and that there could be a race opposing public vs. private initiatives. It would be interesting to study how private companies and nations could be composing an international organization, but, given the current state of space law, companies are not considered as separate entities but as representants of their parent nation. Moreover, many private companies are strong thanks to collaborations and contracts with their nation's space agency, government, or military, so the relationship is more of a partnership than a competition. In any case, should a private company threaten a nation's supremacy or diplomatic relations, most of the company's activities are still Earth-based and it is hard to see how a nation would accept such behaviour, therefore repressing the company's enactments as any other illegal acts. Keeping participation at nation level in the OSA also allows for more flexibility. Nations with an entrepreneurial mindset could put in place a system where their voting power is directly managed by their corporations, while some others might prefer a different approach. The U.S.A. for instance has put in place a national regulation to transfer property and liability of their activities in space to the underlying company doing activities in space. In any case, companies are still paying taxes in their own country, create domestic employment, and participate in economic growth, so all nations will vote in the best interest of their industry.

1.6 Protected Areas

Planetary exploration cannot be wildly conducted, and some rules need to be respected. For instance, the topics of contamination, planetary protection, and preserving scientific integrity, are agreed by everyone to be of top priority, when they are justified. In fact, some of them are included in international treaties, like contamination is mentioned in OST Art. IX [2]. The Moon and Mars hold a lot of scientific value, and some areas should be protected from any interaction to conserve the environment as pristine as possible.

When industries are set up on other planetary bodies, the environment will undergo deep, irreversible changes. Habitat zones will have pipe networks and pressurized environments that will eventually leak. Industrial zones, and especially mines, will modify the terrain. All these installations will also produce waste (unrecycled biological wastes, processed regolith, broken parts, leakages, ...), that will compromise the scientific integrity of some areas, and perhaps make them unusable in the short-medium term. Some historic sites like the Apollo landing sites, as well as the areas surrounding current and past rovers, and well as some identified unique geologic formations, might be suited for protection to prevent them from being tampered. To structure our upcoming use of the resources of the Moon, for instance, a network of “moonways” could be decided, to make sure all commercial transport elements would be taking the same path between 2 industrial sites. This would start discussions about protection of our common lunar heritage and establish a coordination between nations to put in place regulations. Scientific exploration wouldn't need to be regulated, because the number of travels will be less, and they are less likely to repeatedly drive in the same areas.

To address these pollution and preservation issues, several areas shall be defined: habitable areas, restricted areas, scientific areas, waste areas, and moonways. To avoid conflicts of interests, these will have to be defined by another impartial entity, separate from the OSA. Someone without any economic interests. A good candidate for such a task would be the UN, that has a dedicated bureau for space-related issues, the UNOOSA. Prior to defining an area, sample analysis could be performed, when needed, and regularly other samples could also be analysed to monitor the environment's evolution. Those areas are not only required for scientific, regulatory, and ethical reasons, but also for market efficiency reasons. An entity having the monopoly of a given natural resource or location is not desirable, it might as well be regulated and allowed for use under special requests only.

1.7 Space Citizens

A more distant-future prospect, and idealistic suggestion perhaps, would be to put in place a Space Citizenship programme. Astronauts and settlers staying in outer space would likely want to participate in the development of the rules they will live under [6]. Gradually transitioning the decision power to space workers and settlers by providing them with Voice Credits could be desirable. Large contributors to the space development effort residing on Earth could also be considered, as an honorary gift for helping advance humanity’s progress towards the stars.

1.8 Developing countries

Another concern is the inclusion of developing countries in this space expansion movement. The OST states that exploration “shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind”, but the reality is less egalitarian notably when analyzing the lack of implication of African States in space programs. Nigeria is one of the few space nations of this continent and seems to be far from the race of commercialization of space. Algeria is preparing its future law about space operations, but they are likely to give the monopole to the state in these activities. That seems to be a risky bet as the private sector is becoming more and more predominant.

2. Economic structure

How to design an efficient economy for a life-threatening environment in which nothing can be owned? In this section are addressed the following main questions: How to design an economy compliant with the existing regulations? How to benefit from efficient market mechanics without private property? How to bootstrap a space economy from scratch, leveraging the funding capacities of the private sector? How to incentivize space work and settlement for the middle-class, and why is it desirable?

2.1 Partial Ownership

After an internationally recognized authority regulating space exploration is in place (see Governance section 1). An economy whose rules of good conduct are enforced by this authority can be set up. An idea suggested by R. Zubrin in 1995 [7] is to allow Martian land to be sold, leveraging the funds available in the private sector by allowing speculation. However, that could result in inefficient use of land since someone might just buy a land without making use of it, and as discussed previously, according to international agreements [2], nothing can be privately owned, so how could we make those lands available for purchase, and commercial use?

No private property doesn't mean no market. While outer space resources can't be owned, a common interpretation of the OST is that they can be used. The Moon Treaty [8] of 1979 attempts to clarify this point and states that *“States Parties to this Agreement hereby undertake to establish an international regime, including appropriate procedures, to govern the exploitation of the natural resources of the moon as such exploitation is about to become feasible”*. Indeed, rules for governing the use of outer space resources are required, but this treaty does not define them, it only contains an engagement to establish a legal framework as soon as outer space resources exploitation becomes possible. Think about the thin band of land almost permanently illuminated on some mountains or crater rims of the lunar south pole, where the highest concentrations of water have been observed. These lands have special value, and this situation can be transposed to Mars, where geothermal sources and metal deposits will be located. Asteroids are in the same boat. There will be commercial incentives to use outer space resources: an allocation mechanism must be enforced, and a market to dispute the use of those resources could be desirable, as markets come with an efficient allocation of resources.

Harberger licensing [5] is a partial ownership system that allows exposing public goods and government-owned natural resources to the efficiency of allocation provided by market dynamics while preserving the incentives for investment to the current owners, and preventing monopoly (resources locking, or location squatting). Under such a system, owners self-assess the value of their properties and pay a tax proportional to this value. If a buyer is willing to purchase something at the owner's self-assessed price, the owner must cede this good to the buyer. No owner would be ceding a property without being paid what she considers a good price for it, and a counter-claim allowing the owner to raise his self-assessed value to conserve ownership could be put in place. In his Radical Markets book [5], E. Glen Weyl names this tax common ownership self-assessed tax (COST). Such a permanent auctioning system ensures that the person who values the most a property can always benefit from it. This mechanism is already in use for online advertisement space allocation and is particularly adapted to the private exploitation of public goods, such as radiofrequency bands, outer space special locations like geostationary orbits, and celestial bodies surface areas. This system is comparable to licensing but overcome some drawbacks like having to trade-off between allocative efficiency and incentives to invest (you'd want to provide long-term licenses so that owners have an incentive to invest to improve this public good, however, the longer the license, the fewer competitors can challenge the efficient use of the licensed good).

Such a system would be compatible with the Outer Space Treaty [2]. First, there is no appropriation or claim of sovereignty from any nation or company: everything still belongs to the international community (through the OSA). It is only a structure to allocate the use of space resources, that relies on a small tax to introduce market dynamics. That tax benefits everyone who accepts to pay it, as they are also shareholders of the OSA, the entity collecting those taxes. There is no private property, so no right of exclusion, so everyone remains free to access all areas of outer space, if it does not have potential harmful interference with activities of others, as depicted in the OST. The current owner could prevent others from using a property on behalf of harmful interference, but everyone remains free to acquire the use rights of the property, so there is no real exclusion. The collected taxes could also be used to redistribute wealth, if desired, enabling developing countries to catch up in space activities and increasing the number of people working in the space industry, which will result in more innovations for everyone.

2.2 Taxation rate

A recommended COST tax value would be slightly lower than the turnover rate [5]. For example, if a good changes ownership every 15 years or so, it has 6.67% chance to change owner every year, so a 5% annual tax rate is appropriate. Different types of assets (orbits, Moon areas, asteroids, Mars areas, …) have different tax rates, and these rates can be adjusted whenever needed based on observed behaviours, by a vote from the OSA member states. In the first years, the tax rate could be kept very low so that COST values are declared high, and there are not many ownership changes, if any. This would encourage early investments and help cover the initially higher risks involved in financing such projects. In this case, the allocation should be overseen by a separate entity like the UNOOSA, to prevent resource locking and inappropriate allocation. Property could for instance be granted after a given amount of exploration has been performed (imaging, sampling, …).

At a tax rate of 5% for lands, an average Mars price of 1.4$/ha would provide the OSA with 1B$ yearly income. Around 30$/ha, the OSA budget would match NASA's yearly budget. Farmland in France sells between 2k-20k$/ha, but of course, these are open-air breathable areas. No other taxes are required to provide steady income to the OSA, considering the Moon if about the size of the African continent, and there are thousands of asteroids to exploit in the main belt.

2.3 Exceptions

Protected areas, like previous probes landing sites, rovers operating sites, north and south poles, and in general any area deemed protected for scientific, ethical, or any other reason, can't be owned through the partial ownership system, and should require special requests to be issued before any interaction.

2.4 Bootstrapping the private economy

Private companies don't have to wait decades to join the game. With a Partial Ownership system in place, several business models could emerge today, leveraging the private sector funding capacities for a faster space infrastructure development effort and short/medium-term profit perspectives.

Space agencies will contract with major space industry companies to conduct their initial exploration activities, as is the case today. Including them in the process is crucial to prepare the transition to a privately-led economy, because the private sector can acquire knowledge and invest in facilities at a reduced risk. But with a resource utilization regulatory framework in place, start-up initiatives could emerge today, powered by the revolution in space launch costs and funded by audacious investors who see the unparalleled value of space exploitation and settlement. There is no doubt that if the American continent were discovered today, and a property and resource utilization framework could be enforced there, investments would be made to develop this new land of opportunities and support brave pioneers willing to dedicate their lives to the construction of a new world. Nations would have strategic interests in establishing facilities and a robust presence on this new continent and would do so. It is often said that the Moon is Earth's 8th continent, and with the ever-increasing reliability of space technologies and decreasing costs of making space hardware, it is becoming more and more evident that the last thing required for developing a sustainable human presence in space is a robust international legal framework. Mars is even easier to access than the Moon due to its atmosphere, and the resources available there arguably make it an even safer and more sustainable destination. After Mars has been tamed, supporting operations to the Asteroid belt will be more convenient and economic.

When a private company conducts geological surveys on the Moon, Mars, or Asteroids, they become aware of valuable locations holding useful materials. This information can be sold to the scientific community or stimulated a through bounty-based system. With the partial ownership system in place, the company can acquire the land, then increase the self-assessed value of these locations, in the prospect of future interested buyers. A business model for exploration companies can be supported. Similarly, other companies will wait for valuable locations to be discovered and buy these locations to send mining equipment that will perform resources extraction. Transport companies will be established to move all these extracted resources back to Earth orbit, the Moon, or to future Mars settlement areas, where other companies will be preparing the terrain, and building power distribution and piping networks. A whole private economy can be bootstrapped, the only missing element is a resource allocation framework.

2.5 Social dividend

Some profits collected through the COST tax system could be redistributed as a universal basic income to space workers and settlers, providing them with a substantial amount of money. This would ensure that the expensive daily goods in space can be afforded by people living there. This is a very important point because life in space will be expensive and high-paying jobs or other sources of income are needed to make the trip appealing to the middle-class. Without high incomes in space, only tourists and individuals mandated by their employers (or military) will be able to make the trip. Providing space workers and settlers with a social dividend is a way for space capital holders to commonly incentivize migration to their land, and finance economic growth, because in the labour-short space economy, the limiting factor for expansion will be the number of people able to travel and live there.

The taxes collected through the COST system could also serve to build investment funds for supporting the new space start-up ecosystem and redistribute wealth so that over a very long period, the inequalities of starting capital will be evened out, and truly everyone can acquire the capacity to dispute the use of space resources, guaranteeing an effective resource allocation and an efficient space economy.

3. Conclusions

A brief overview of space law has been made, both through international treaties and national laws. It has been discussed how existing analogous situations to space, like the isolated, scientifically interesting, and resources-rich Antarctica, can be used as inspiration to establish an international legal framework to govern the use of outer space resources. A governance system based on the foundation of a new intergovernmental entity has been proposed, and its internal decision process based on radical democracy is depicted as a powerful tool to establish an international legal framework and regulate the use of common resources. The protection of our common lunar heritage is discussed, and a system based on protected areas like on Earth is proposed. A program of space citizenship is proposed to gradually transfer the governance power of space settlements from Earth-bound nations to new space-faring branches of human civilization gradually

AD ASTRA – IAC Special Issue – 2019

earning its independence. An economic structure based on partial ownership and the establishment of a Harberger tax is described, and it is shown that such mechanism would allow to benefit from the efficient allocation of market dynamics, while respecting the international agreements that prevent private property and claims of sovereignty, keeping the ownership of space resources shared between all space-faring nations.

References

[1] Global Exploration Roadmap (GER) from the International Space Exploration Coordination Group (ISECG), January 2018.

[2] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, 1966.

[3] About UN Membership, on the United Nations website, http://www.un.org/en/sections/member-states/about-un-membership/index.html, (accessed 21.06.19).

[4] Lalley, Steven P., and E. Glen Weyl. 2018. "Quadratic Voting: How Mechanism Design Can Radicalize Democracy." AEA Papers and Proceedings, 108: 33-37.

[5] Radical Markets, Eric Glen Weyl and Eric Posner, 2017.

[6] T. Cheney, "Space Settlement Governance: An Overview of Legal and Policy Issues", 2019.

[7] R. Zubrin "The Economic Viability of Mars Colonization", 1995.

[8] Agreement Governing the Activities of States on the Moon and Other Celestial Bodies, 1979.

IAC-19-D3,IP,5,x5244

Modular Field Robots for Extraterrestrial Exploration

Troy Cordie[a,b], Ryan Steindl[a], Ross Dungavell[a], Tirthankar Bandyopadhyay[a]

[a] *The Robotics and Autonomous Systems Group, CSIRO, Pullenvale, QLD 4069, Australia.*
[b] *The Robotics and Autonomous Systems Group, Queensland University of Technology, Brisbane, QLD, 4000, Australia*

Abstract

Modular design methodology enables rapid reconfigurability for functional changes, robustness to failures and space utilisation for transportation. In the case of planetary exploration robots, there is promise in modular robots that are able to reconfigure itself for exploration of unknown terrains.

This paper presents a design and controller architecture for modular field robots that can be rapidly assembled in a variety of functional configurations. A key challenge of building a functional robot out of modular units is the ability to seamlessly add, remove and replace individual units to enable functional improvements as well as adapt to terrain requirements. An added benefit of modularity is the ability for graceful degradation through reconfigurability such as detaching a module or adaptation of motion models to actuator failure.

We present a representative modular wheel design and a distributed controller architecture able to create a range of bespoke multi-wheeled configurations capable of traversal on a variety of terrains during simulated failure scenarios. The self-contained wheeled unit has energy, computation communication, and actuation modules and does not require any modification or physical customization in the field during deployment enabling a seamless plug and play behaviour. The hierarchical control structure runs a body controller node that decomposes a whole body motion requested from a higher level planner to generate a sequence of actuation goals for each of the modules, while a local controller node running on each of the modules ensures that the desired actuation is adapted to the configuration, load and terrain characteristics.

Keywords: (Mobile robots, Robot motion, Unmanned autonomous vehicles, Modular robotics, Graceful degradation)

Nomenclature

- V_B= Velocity of the robot body.
- r_(a1/B)= Radius from the robot body to actuator 1
- θ= Angle from the body to the wheels reference frame
- β= State of steering actuator
- φ= State of drive actuator
- NW_n= State of an individual NeWheel
- NR= State of robot instance

Acronyms/Abbreviations

- (ICR) Instantaneous centre of rotation
- (URDF) Unified Robot Description Format

1. Introduction

Robotic platforms deployed for extraterrestrial exploration have no capacity for repair or replacement parts. This isolation means that any problem encountered needs to be overcome to keep the mission alive. The Mars rover has faced problems including actuator failure and becoming bogged in the terrain. When the mission has been able to continue a compromised control strategy has been adopted, such as dragging a wheel. Though when strategies to free a platform have been unavailable missions have ended. This paper proposes the use modular wheels to overcome some of the problems encountered on such missions. The position independent nature of the actuators allows the nominal front of the platform to shift, allowing operations with failed actuators. While modularity enables the platform to continue operations after suffering a trapped or failed module ejecting the impacted component from the system. The NeWheel system see Figure 1 offers a test bed for developing this style of behaviour.

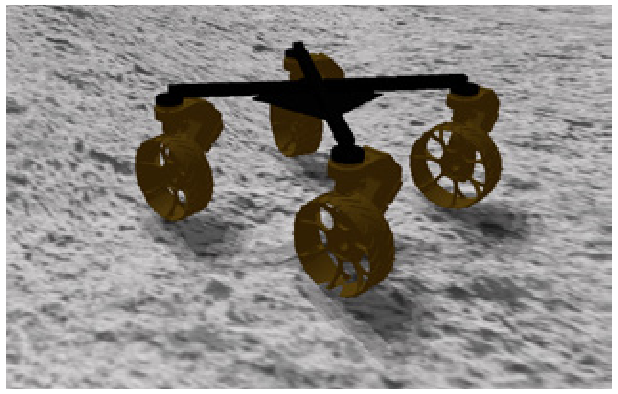


Figure 1. NeWheel platform depicted in Gazebo simulation Moon analogue.

The remainder of the paper is structured as follows: Section 2 explores the existing literature of modular robotics and their applicability to extraterrestrial exploration. Our strategy for platform adaptation to failure is laid out in section 3. Section 4 introduces the modular wheel system used in both simulated and hardware testing conducted for this paper with an overview of the controller and its ability to adapt. Testing was primarily carried out in simulation and is detailed in section 5 with some of the testing repeated on the platform in section 6 , and lastly, section 7 summarises the results of this paper.

2. Literature

Since the Russian Lunokhod-1 rover landed on the surface of the moon in 1971 [1] humans, have sent robotic rovers to extraterrestrial bodies to explore and send back data. These rovers cut off from maintenance and repair survive until their sensors and actuators age and decay to a point they are no longer able to operate. Mars rovers Spirit and Opportunity far exceeded their battery life expectancy but at the end of their mission began to reach the limits of their actuators and sensors. In the course of their mission both suffered failures resulting in the need to change control strategies as noted by Townsend [2]. These changes included driving both platforms backwards for large parts of their deployment. For Spirit, this was to reduce the drag of a misaligned wheel and, in the case of Opportunity, to reduce loading on a damaged wheel [3]. Spirit survived with approximately 17% less efficiency until 2009 when it became bogged in soft soil and became a static science platform before finally becoming uncontactable in 2010.

The class of wheeled legged robots shows promise to overcome some of these challenges. In this area, designs vary substantially with each wheeled legged platform proposing different configurations and degrees of limb articulation. Wheeled legged platforms offer the ability to reconfigure platform characteristics such as footprint, ground clearance and body pose. These platforms include All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) [4] and [5], The Mars Analog

Multi-Mode Traverse Hybrid (MAMMOTH) [6] and [7], Scarab lunar drilling rover [8] and Wheeled Actively Articulated Vehicle (WAAV) [9] and [10]. Multiple versions of the kinematic for such reconfigurability exist including the work by Alamdari [11], [12] and [13], Sreenivasan [14] as well as the generic models such as [15] by Kelly. By reconfiguring the limb attached to a damaged wheel, the platforms could continue without the misaligned wheel suffered by Spirit. Additionally, the wheeled leg class of platforms has demonstrated the ability to walk out of situations when wheels become bogged or the terrain difficult to pass. This concept has been shown by Klamt [16]. Wheeled legged platforms show promise and have demonstrated capabilities that could have overcome the scenario that trapped Spirit. This additional reconfigurability comes at the cost of mass, energy usage and complexity. The addition of legs to the platform also adds additional motors sensors and locking mechanisms [17] with each of these adding weight a consideration for transportation to the surface and while deployed as noted by [4]. All of these platforms would, however, suffer the same fate as Spirit should a wheel become stuck - relegated to a static sensing platform.

This paper proposes combining the benefits of reconfigurability with the noted ability of modular robot systems to gracefully degrade [18], [19]. In their simplest form, Murphy [20] describes modular robots as a mother robot with a deployable daughter platform. This style of mother and daughter deployment will be seen on Mars with the planned 2020 Mars helicopter [21].These platforms have also shown that by reconfiguring, a system can produce platforms with distinctly different capabilities with the same components [22], [23].

At the other end of complexity and component numbers are the modular systems comprised solely of homogenous modules. Systems such as Superbot [24], [25] and SMORES-EP [26], [27] modules illustrate the possibilities of modular, reconfigurable systems. Each of the Superbot and SMORES-EP systems allows multiple platform configurations capable of performing simple tasks. As noted in [26], these systems reach hardware limitations with the example of SMORESEP capable of supporting 3.1 of its modules when cantilevered restricting the size and the maximum number of components deployed.

Platforms such as Snapbot [28], [29], [30] and Snake Monster [31] connect modular component around a purpose designed torso. Both platforms demonstrate mobility with different numbers of modules attached. This functionality would allow these platforms to abandon failed or faulty modules to maintain system functionality. The torso on both Snapbot and Snake Monster presents a single point of failure. As the torso provides all of the communication and planning for the limbs, its failure would stop any further function. This work looks to incorporate the platform reconfigurability of wheeled legged platforms with the ability to abandon faulty modules from a dumb torso of modular robotics. This combined strategy is laid out in the following section proposing platform adapting until the deployment is risked and ejecting modules if required.

3. Strategy for robustness

A reconfigurable modular wheeled platform deployment faced with actuator failure could eject the defective wheel and continuing as an n-1-wheeled platform. While this approach is a core strategy for proposed for modular robots deployed in the field, it represents a loss of hardware and would be avoided if possible. Retaining equipment is the priority until it represents a risk to the mission. This work explores strategies to keep defective wheels through some potential failure modes. The potential failure modes are: the failure of the drive motor, failure of the steering motor and the combined failure of the steering and drive motors. In plots and figures depicting the robot’s configuration an actuator failure is indicated with either the failed steering or the failed drive icons seen in Figure 2. Figure 3 is a decision tree for the transition from four fully functional wheels to a partially functional three-wheeled platform. Failure responses have been explored for the four and three-wheeled systems as they have the least ability to reconfigure by removing a wheel. These two configurations are reflective of the last remaining components as the system fails or an exploratory platform cut off from replacement parts.

Figure 2: Icons indicating failure of an actuator from left to right: failure of a steering actuator, failure of the drive actuator.

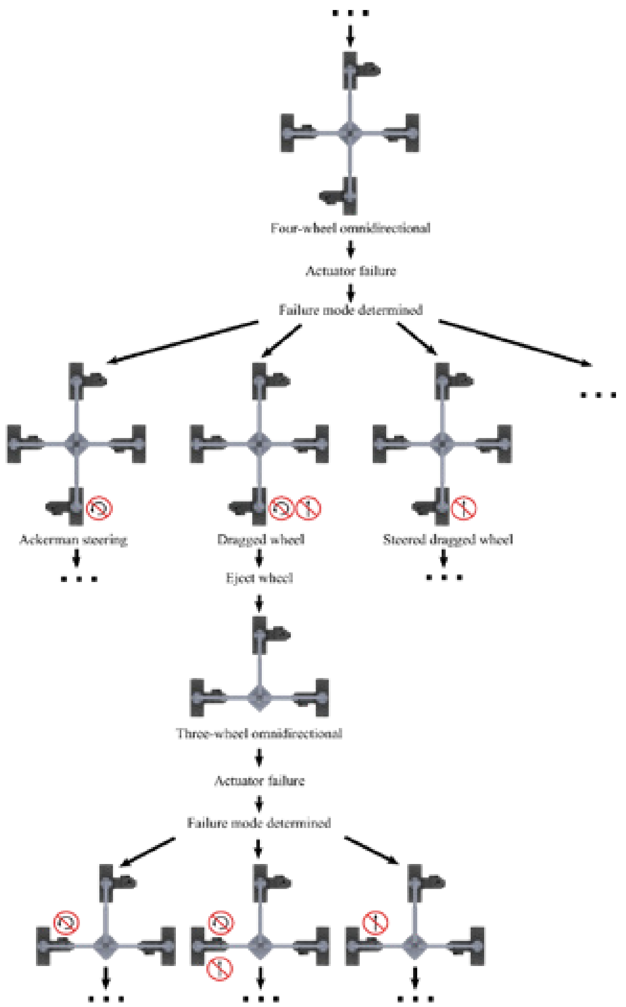


Figure 3: Partial diagram of a four-wheeled modular robot decaying to the point of ejecting a wheel. Followed by the failure of a module in the three-wheeled platform.

The proposed strategy retains partially damaged or broken wheels through adapting the control strategy based on the hardware available. Read from the top Figure 2 proposes an omnidirectional control strategy for a platform with functional wheels. As failure modes are detected, the appropriate motion mode is adopted. In the case of the failed steering/drive motor, the dragged wheel strategy is proposed. If this wheel becomes a liability, it can be ejected from the system producing a three wheeled platform capable of omnidirectional motion. The remaining three-wheeled platform has scope to cope with failed actuators.

Edge cases for this proposed strategy are numerous and will not be explored in this work. Situation and platform dependent solutions would be required.

4. NeWheel (Any Wheel)

The NeWheel system has been designed to allow fast reconfigurability before or during deployment. This reconfigurability is variable size, shape and module numbers within the system and not dependent on symmetric configurations. These configurations range from large numbers of wheels working collaboratively to individual wheels operating with passive wheels. When combined in large groups the NeWheels could move heavy objects or if combined with rocker bogie links could explore the surface. When a single NeWheel is combined with two passive wheels a tricycle motion model is developed requiring the least power of all the configurations. Previous work carried out with the NeWheel system demonstrated its ability to operate in different configurations and be rapidly redeployed when inspecting dilapidated buildings [32]. The following sections introduce the wheels and controller to demonstrate our proposed strategy possible.

4.1 Modular Wheels

The NeWheel modules are self-contained, two degrees of freedom powered caster wheels as seen Figure 4. First introduced in [33] each wheel achieves the desired velocity and steering angles with the use of two onboard motors, a battery and onboard computing. In addition to controlling driving and steering velocity, the onboard computer permits inter-wheel communication via WiFi. The location of the power supply and computing on the link between the steering and the driving motors allow the body-wheel connection to rotate continuously. The use of 3D printing has allowed for rapid replacement of parts and design modifications between iterations.

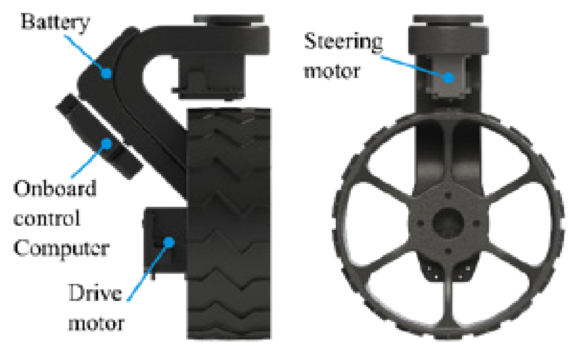


Figure 4: Current iteration of the NeWheel module.

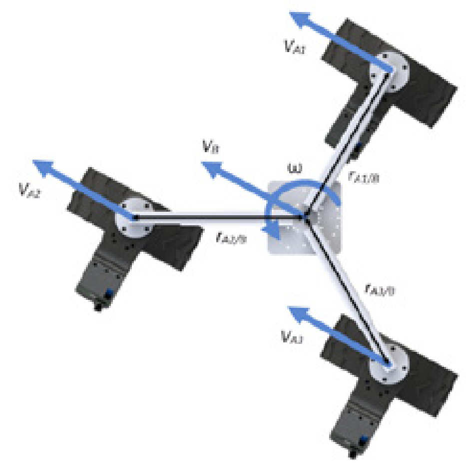


Figure 5: NeWheel platform configured with the instantaneous centre of rotation at the centre of three wheels. The combined velocity of the three connected wheels produce the desired linear and angular velocity of the body.

4.2 Controller

The controller designed for the NeWheel system is central to the system's ability to reconfigure quickly and redeploy. It is based around a parametric robot model that once modified propagates through the remainder of the system and generates the controller. The generated controller maintains body velocity by calculating the relative velocity of each wheel see equations 1 and 2. Each wheel independently maintains its own desired velocities and heading, Figure 5 shows three NeWheels achieving the desired body linear and angular body velocity.

$$v_{wi} = v_B + \omega_B \times R_{wi/B} \tag{1}$$

$$\alpha_{wi} = \alpha_B + \omega_B^2 \times r_{wi/B} + \omega_B \times (\omega_B \times r_{wi/B}) \tag{2}$$

The implementation of a velocity controller allows movement of the nominal centre of the platform or instantaneous centre of rotation (ICR). Moving the ICR produces different platform behaviour from the same configuration with the same input velocities emulating multiple motion models. Locating the ICR centrally between the wheels attached to the platforms allows Non-holonomic Omnidirectional motion within the body of the platform, as seen in the top left of Figure 6. The top right of Figure 6 show the ICR located on the axis of rotation of the rear wheels, by restricting the control input to$[x,\theta]$ produces a platform with Ackerman steering. Similarly, tricycle steering is produced in platforms with three-wheels see the bottom right of Figure 6. Finally, by configuring IRC between both pairs of wheels sets the platform as differential drive or skid steer see the bottom left of Figure 6.

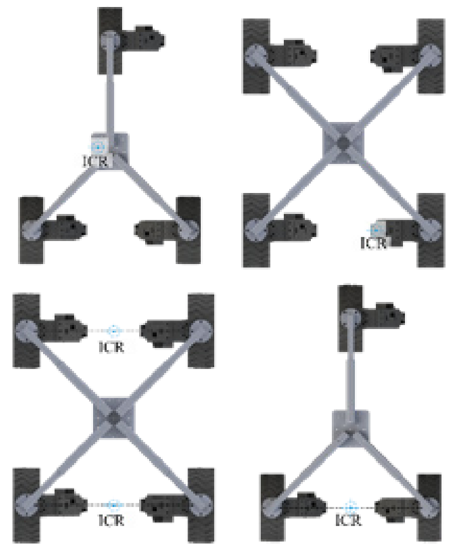


Figure 6: Clockwise from top left: ICR placed centrally between all attached wheels producing non-holonomic omnidirectional configuration. ICR placed in line with the drive axis of the rear two wheels of a four-wheeled platform confining the platform to Ackerman control. ICR placed in line with the drive axis of the back two wheels of a three-wheeled platform restricting the platform to tricycle control. ICR located between both sets of wheels produces differential drive or skid steer

$$\zeta_O = \int R(\theta)^{-1} J_1(\beta)^{-1} J_2 \dot{\phi}\, dt \tag{3}$$

The forward kinematics are derived in equation 3 where $R(\theta)^{-1}$ is the homogeneous transform matrix between the robots pose and the world frame. $J_1(\beta)$ is the $n \times 3$ matrix with each row containing the kinematic constraints of a wheel see equation 4. The pseudo inverse taken to achieve $J_1(\beta)^{-1}$. Where θ_n is the angle from the body to the wheels frame of reference and β_n is the heading of individual wheels.

$$J_1(\beta) = \begin{bmatrix} \sin(\theta_1+\beta_1) & -\cos(\theta_1+\beta_1) & -l\cos(\beta_1) \\ \sin(\theta_2+\beta_2) & -\cos(\theta_2+\beta_2) & -l\cos(\beta_2) \\ \vdots & \vdots & \vdots \\ \sin(\theta_n+\beta_n) & -\cos(\theta_n+\beta_n) & -l\cos(\beta_n) \end{bmatrix} \quad (4)$$

Under regular operation the steered wheels $J_1(\beta)$ of each wheel is the time-varying function $J_1(\beta_s)$ updating the rotation of the wheels at each time step see equation 5. Wheels with a failed steering actuator have the corresponding $J_1(\beta)$ row $J_1(\beta_f)$ representing a fixed joint as indicated by equation 6.

$$J_1(\beta_s) = [\sin(\theta_{b1}+\beta_{sn}) \quad -\cos(\theta_{b1}+\beta_{sn}) \quad -l\,cos(\beta_{sn})] \quad (5)$$

$$J_1(\beta_f) = [\sin(\theta_{b1}+\beta_{fn}) \quad -\cos(\theta_{b1}+\beta_{fn}) \quad -l\,cos(\beta_{fn})] \quad (6)$$

$$J_2\dot{\varphi} = \begin{bmatrix} r_1 & 0 & \cdots & 0 \\ 0 & r_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & r_n \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{\phi} \\ \vdots \\ \dot{\phi} \end{bmatrix} \quad (7)$$

Equation 7 is comprised of the $n \times n$ diagonal matrix J_2 of wheel radiuses r_n and the column vector of n length $\dot{\phi}$ containing wheel velocities. For the remainder of the paper, the platform state is described in terms of the actuator input variables β and ϕ. Where β is either the variable β_s for a steerable wheel or $\boldsymbol{\beta_f}$ for a failed actuator or fixed wheel. The variable ϕ describes the state of the drive motor for each NeWheel, with $\dot{\phi}$ denoting a functioning wheel and $\boldsymbol{\phi_f}$ indicating a failed actuator. Individual wheels are noted by the vector $NW_n=[\beta\ \phi]^T$ with a platform ($NeRobot$) defined by a combination of wheel vectors NR. The example below NW_1 as functional while NW_2 has a failed steering actuator, NW_3 a failed drive actuator and NW_4 represents a failure of both the steering and drive actuators.

$$NR = \begin{bmatrix} \beta_s & \boldsymbol{\beta_f} & \beta_s & \boldsymbol{\beta_f} \\ \dot{\phi} & \dot{\phi} & \boldsymbol{\phi_f} & \boldsymbol{\phi_f} \end{bmatrix} \quad (8)$$

4.3 Simulations

Experimental results have been captured in the gazebo physics simulator. The simulator uses the parametric Unified Robot Description Format (URDF) model developed for the NeWheel. Allowing fast testing of a variety of different platform configuration. Each simulation starts with the platform pose $\zeta\_0=[0\ \ 0\ \ 0]^T$ in the units $\zeta\_0=[xm\ \ ym\ \ \theta rad]^T$ and a goal set of $\zeta 1=[5.0\ \ 5.0\ \ 3.14]^T$. A simple reactive planner guides the platform from the start to the goal position. The start point, goal and level ground terrain were selected to highlight the different platform behaviour available within the same platform configurations by shifting the nominal centre of the platform. This experimental setup limits the variables to the number of wheels attached to the platform and the ICR. Figure 1 shows the four NeWheeled platform in Gazebo.

5. Experimentation

5.1 Non-holonomic omnidirectional

$$NR = \begin{bmatrix} \beta_s & \beta_s & \beta_s & \beta_s \\ \dot{\phi} & \dot{\phi} & \dot{\phi} & \dot{\phi} \end{bmatrix} \quad (9)$$

or

$$NR = \begin{bmatrix} \beta_s & \beta_s & \beta_s \\ \dot{\phi} & \dot{\phi} & \dot{\phi} \end{bmatrix} \quad (10)$$

An NeWheel platform is capable of non-holonomic omnidirectional motion with any number of functional modules connected. The robot states 9 and 10 show examples of all of the actuators functional for the three and four wheeled configurations. This motion is made possible by the NeWheels drive actuators alignment with the steering actuator allowing the platforms to turn its wheels without moving. For this control strategy, the instantaneous centre of rotation is located centrally between the NeWheels units. This freedom of movement allows manoeuvres such as orientating itself to the goal heading as it approaches the target. An example of this behaviour shown in Figure 7 on a three-wheeled platform. The platform starts with the pose $[0.0,0.0,0.0]^T$ and travels to the goal pose of [5.0,5.0,3.14] T. The platform achieves this trajectory by rotating its body as it travels along the desired path.

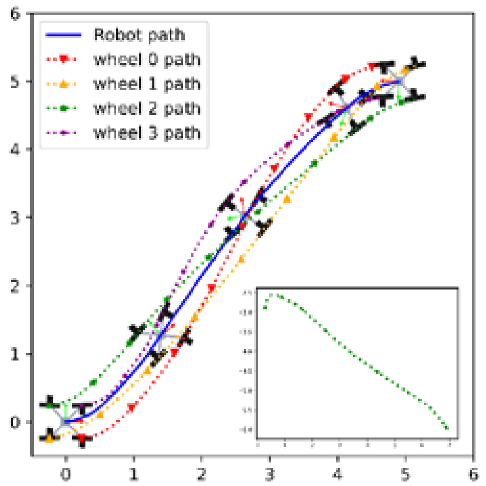


Figure 7: Four NeWheels moving to the pose $[5.0\ \ 5.0\ \ 3.14]^T\,[m\ \ m\ \ rad]^T$. The insert depicts the orientation of wheel 2 relative to the platform as it performs the manoeuvre.

5.2 Ackerman steering

$$NR = \begin{bmatrix} \beta_s & \beta_s & \boldsymbol{\beta_f} & \beta_s \\ \dot{\phi} & \dot{\phi} & \dot{\phi} & \dot{\phi} \end{bmatrix} \quad (11)$$

or

$$NR = \begin{bmatrix} \beta_s & \beta_s & \boldsymbol{\beta_f} \\ \dot{\phi} & \dot{\phi} & \dot{\phi} \end{bmatrix} \quad (12)$$

The failure of a steering actuator as seen in robot configurations 11 and 12 on a robot platform deployed with NeWheels removes a degree of freedom from the platform described previously. This failure prevents the platform from moving perpendicular to the heading of the damaged wheel. An Akerman style motion model is employed to accommodate the loss functionality, minimising the impact on the system. The nominal platform centre is moved to a point along the failed wheels drive axis of rotation to achieve this change in the controller. When the centre is relocated, the symbolic front of the platform passes through the new centre point parallel to the heading of the affected wheel see Figure 9. The remaining NeWheels maintain their full functionality adopting the required heading for driving and steering. Restricting control input for the y-axis (lateral motion) and remapping it as angular velocity results in the platform rotating on the spot to orientate the platform in the desired direction. This functionality, typically not seen in platforms implementing Akerman steering, allows the platform to continue operation in confined spaces. Figure 8 shows a platform moving to the same final pose $[5.0\ \ 5.0\ \ 3.14]^T$ as Figure 7 while using the Akerman strategy.

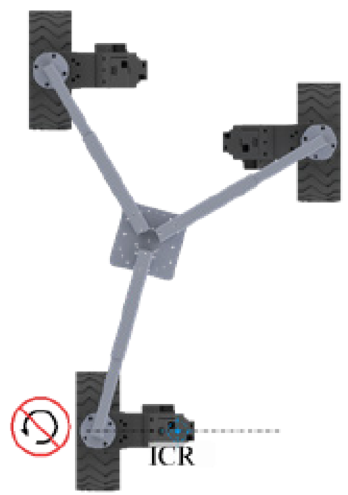


Figure 8: Robot configured to align with the failed steering actuator on the back of a three-wheeled platform.

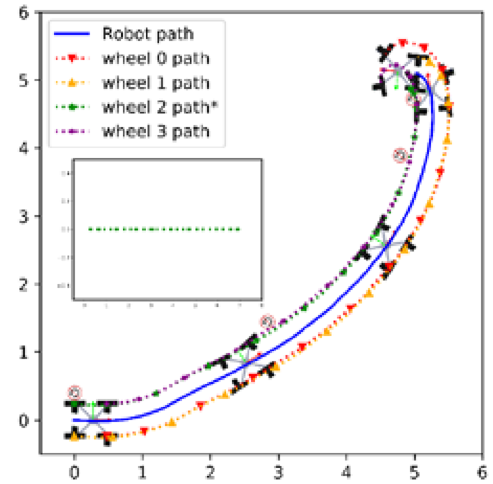


Figure 9: Four NeWheels moving to the pose $[5.0\ \ 5.0\ \ 3.14]^T\,[m\ \ m\ \ rad]^T$ using the Ackerman motion model. The insert depicts the orientation of wheel 2 relative to the platform as it performs the manoeuvre.

Robot configurations 11 and 12 showing the third NeWheel failing is only indicative. Due to the platforms ability to reconfigure a steering failure is accommodated in any of the wheels by changing the nominal front for the platform. This strategy works for symmetric and nonsymmetric platforms alike. In the case of a three-wheeled platform, the resultant platform will operate as either a tricycle with a single steered wheel or with Ackerman style steering and a single fixed wheel.

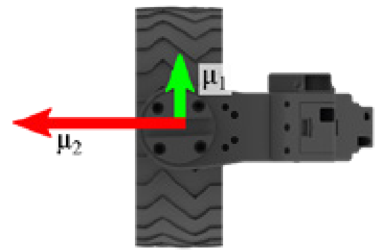


Figure 10: Assumed friction when dragging dead wheel.

5.3 Steered dragged wheel

A steered dead wheel could take many forms and assumptions for this work are as follows. The drive motor is locked in place with no or minimal ability to move, while the steering motor has retained full functionality. The friction model of the wheel/surface follows Figure 10 where dragging the wheel perpendicular to the axis of rotation incurs the least friction penalty. Similar to the failed steering actuator in Section 5.2 the location of the failed drive actuator in the robot states 13 and 14 is only indicative due to systems ability to re-orientate.

$$NR = \begin{bmatrix} \beta_s & \beta_s & \beta_s & \beta_s \\ \dot{\phi} & \dot{\phi} & \dot{\phi} & \boldsymbol{\phi_f} \end{bmatrix} \quad (13)$$

or

$$NR = \begin{bmatrix} \beta_s & \beta_s & \beta_s \\ \dot{\phi} & \dot{\phi} & \boldsymbol{\phi_f} \end{bmatrix} \quad (14)$$

Under the conditions of the single drive motor failure, the platform retains the ability to re-orientate the failed wheel with the direction of travel. When the desired velocity has only a linear component and no angular velocity. The orientation of the platform is modified, locating the dead wheel between the remaining wheels as shown in Figure 11a. Allowing the resulting force from the dragged wheel to be distributed between the remaining wheels. Equation 15 is force required to overcome the force induced on the system by the dead wheel where F_f is the force created by the dead wheel dragging and F_{di} is the individual force of the functional wheels.

$$F_f = \sum\nolimits_{i=1}^{n} F_{d_i} \quad (15)$$

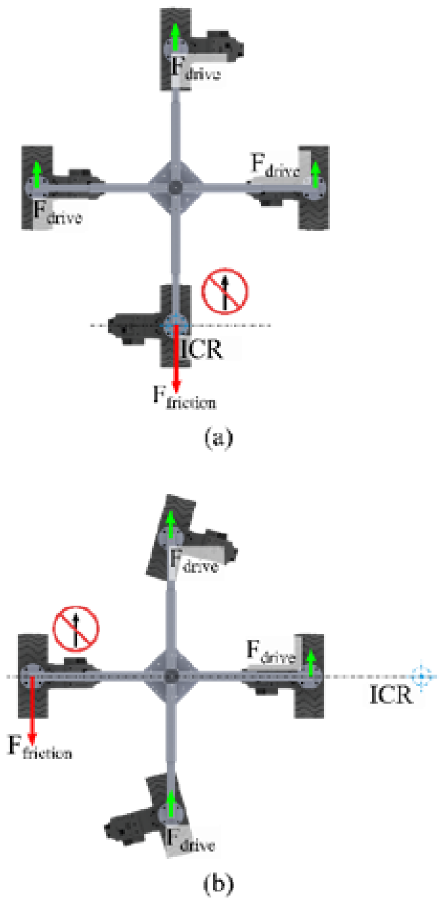


Figure 11: A four-wheeled configuration with a failed drive actuator (a) shows the platform reorientated to travel without angular velocity and (b) depicts the platform rotating.

When rotating the platforms ability to shift the ICR allows a platform with a failed drive actuator to shift the ICR outside the body of the robot. Shifting the ICR away from the failed wheel allows management of the torque required of the functional wheels refer to Figure 11b. This system behaviour is captured by equation 16 with the torque on the system generated by the dead wheel $F_f \times r_f$ is counteracted by the torque created by the remaining wheels $F_{di} \times r_{di}$. Where Ff is the force generated by dragging the dead wheel, r_f is the radius from the ICR to the failed wheel, F_{di} is the force generated by individual functional wheels and rdi is the radius from the ICR to the individual functional wheels. The two scenarios above assume the remaining wheels can overcome the forces generated by the failed wheel dragging. The remaining wheels must still produce a functional platform for this strategy to be viable. In the scenario where dragging the failed wheel jeopardises the deployment, the option to eject the wheel must be considered.

$$F_f \times r_f = \sum\nolimits_{i=1}^{n} F_{d_i} \times r_{d_i} \quad (16)$$

5.4 Dragged wheel

The failure of the drive and steer motors leaves the platform with a dead wheel see robot models 17 and 18. Unlike the steered dragged wheel, the platform must reconfigure using the remaining wheels to minimise the impacts of dragging the dead wheel. This scenario leaves the platform unable to distribute the forces between the remaining wheels evenly. This strategy would be considered before ejecting a wheel from a system few remaining modules.

$$NR = \begin{bmatrix} \beta_s & \beta_s & \beta_s & \boldsymbol{\beta_f} \\ \dot{\phi} & \dot{\phi} & \dot{\phi} & \boldsymbol{\phi_f} \end{bmatrix} \quad (17)$$

or

$$NR = \begin{bmatrix} \beta_s & \beta_s & \boldsymbol{\beta_f} \\ \dot{\phi} & \dot{\phi} & \boldsymbol{\phi_f} \end{bmatrix} \quad (18)$$

6. Platform Testing

Previous testing of the NeWheel platform has demonstrated the system's ability to be rapidly deployed into unstable buildings [32]. This work involved deploying the platform into a decaying building to map and collect data. This work also demonstrated the different capabilities of platform configurations, three-NeWheeled omnidirectional and single NeWheel and two passive wheeled tricycle. This testing showed the tricycles ability to operated on flat terrain and slopes without loose surfaces. Loose ground, and steep slopes proved too much for the tricycle while the three-NeWheeled omnidirectional platform performed minimal slip.

Testing for this paper used a custom built aluminium

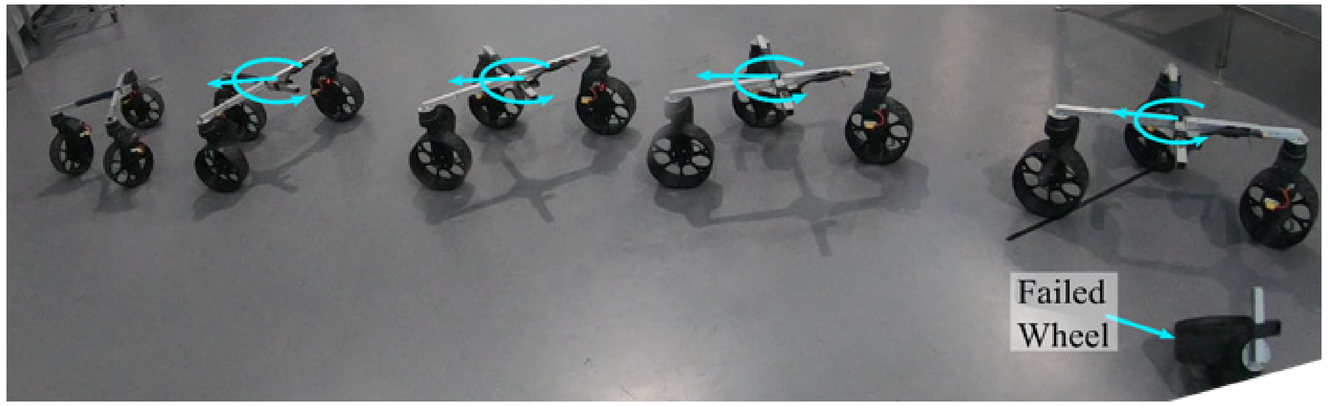


Figure 12: NeWheel platform testing, the fourth failed wheel is ejected and the three-wheeled continues.

frame with options for three and four-wheeled configurations. Each wheels configuration within the body can be adjusted radially around the base and the body/wheel links are discretely adjustable in 20 mm increments. This adaptability allows testing of configurations with different sizes, shapes and wheel numbers.

Initially, the platform configured with four functional NeWheels with the ICR placed between them. Commanded to the position $[3.0, 3.0, 3.14]^T$ the system drove to the desired location using the non-holonomic omnidirectional motion model, this was repeated twice more with simulated failure to a steering motor and drive motor. During the failed steering test, the platform drove to the desired pose using an Ackerman control strategy. The final test with the dead drive motor saw the platform struggle to rotate the through 180° for the final pose. Resetting to the pose to $[0 \;\; 0 \;\; 0]^T$ the module with the failed drive motor was uncoupled. The platform drove away from the fourth wheel achieving the desired pose in a non-holonomic omnidirectional manner see Figure 12.

7. Conclusion

This work has proposed a framework for continued operations of reconfigurable modular robots deployed on extraterrestrial bodies. The work noted that wheeled legged platforms enabled some of the proposed functionality at the cost of complexity and mass. Their reconfigurability, combined with wheeled modular robotic units enables the proposed strategy. The strategy laid out proposes modifying the motion model of the deployed platform as actuators decay. Once a module becomes a liability to the mission, modularity allows its removal from the system. The system used to demonstrate this framework was the NeWheel modular robot system; the robot system's hardware and controller having been specifically developed for rapid reconfigurability. The controller's ability to move the instantaneous centre of rotation allows the motion model of the system to change without modifying the hardware. Proposed solutions to steering and drive failures have been tested in both a simulated and simple environment on the robot. The results demonstrated the ability to change the motion model of the platform without needing the modify its configuration. These proposed failures only cover a small number of the possible failures suffered by a deployed platform. Future work includes the automatic adaptation to failure and exploration of further failure modes. In conclusion, reconfigurable modular robots, such as the NeWheel, offer solutions to potential challenges for humanity exploring extraterrestrial bodies.

Acknowledgments

The work in this project was fully funded by the CSIRO Robotics and Autonomous Systems Group. All correspondence should be addressed to troy.cordie@csiro.au or tirtha.bandy@csiro.au

References

[1] S. Kassel, “Lunokhod-1 Soviet Lunar Surface Vehicle.” 1971.

[2] J. A. Townsend et al., “Mars Exploration Rovers 2004-2013: Evolving Operational Tactics Driven by Aging Robotic Systems,” 2014.

[3] R. Showstack, “Mars Rover Enters New Phase of Mission,” Eos, Trans. Am. Geophys. Union, vol. 91, no. 5, pp. 44–44, Feb. 2010.

[4] B. H. Wilcox et al., “ATHLETE: A cargo handling and manipulation robot for the moon,” J. F. Robot., vol. 24, no. 5, pp. 421–434, May 2007.

[5] A. S. Howe, B. Wilcox, M. Barmatz, and G. Voecks, “ATHLETE as a Mobile ISRU and Regolith Construction Platform,” Apr. 2016.

[6] W. Reid, F. J. Perez-Grau, A. H. Goktogan, and S. Sukkarieh, “Actively articulated suspension for a wheel-on-leg rover operating on a Martian analog surface,” in Proceedings - IEEE International Conference on Robotics and Automation, 2016, vol. 2016-June, pp. 5596–5602.

[7] W. Reid, A. H. Göktoğan, and S. Sukkarieh, “Moving mammoth: Stable motion for a reconfigurable wheel-on-leg rover,” in Australasian Conference on Robotics and Automation, ACRA, 2014.

[8] P. W. Bartlett, D. Wettergreen, and W. Whittaker, “Design of the Scarab Rover for Mobility & Drilling in the Lunar Cold Traps,” Int. Symp. Artif. Intell. Robot. Autom. Sp., pp. 3–6, 2008.

[9] S. V. Sreenivasan, P. K. Dutta, and K. J. Waldron,

"The Wheeled Actively Articulated Vehicle (WAAV): An Advanced Off-Road Mobility Concept," in Advances in Robot Kinematics and Computational Geometry, Dordrecht: Springer Netherlands, 1994, pp. 141–150.
[10] S. V. Sreenivasan and K. J. Waldron, "Displacement Analysis of an Actively Articulated Wheeled Vehicle Configuration With Extensions to Motion Planning on Uneven Terrain," J. Mech. Des., vol. 118, no. 2, pp. 312–317, 1996.
[11] A. Alamdari and V. N. Krovi, "Design of articulated leg–wheel subsystem by kinetostatic optimization," Mech. Mach. Theory, vol. 100, pp. 222–234, Jun. 2016.
[12] A. Alamdari and V. Krovi, "Active Reconfiguration for Performance Enhancement in Articulated Wheeled Vehicles," no. 46193. p. V002T27A004, 2014.
[13] A. Alamdari, X. Zhou, and V. N. Krovi, "Kinematic Modeling, Analysis and Control of Highly Reconfigurable Articulated Wheeled Vehicles," in Volume 6A: 37th Mechanisms and Robotics Conference, 2013, p. V06AT07A070.
[14] S. V. Sreenivasan and B. H. Wilcox, "Stability and traction control of an actively actuated micro???rover," J. Robot. Syst., vol. 11, no. 6, pp. 487–502, 1994.
[15] A. Kelly and N. Seegmiller, "Recursive kinematic propagation for wheeled mobile robots," Int. J. Rob. Res., vol. 34, no. 3, pp. 288–313, Mar. 2015.
[16] T. Klamt and S. Behnke, "Anytime hybrid driving-stepping locomotion planning," in 2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2017, pp. 4444–4451.
[17] J. A. T. Machado and M. F. Silva, "An Overview of Legged Robots," Int. Symp. Math. methods Eng., 2006.
[18] M. Yim et al., "Modular self-reconfigurable robot systems [Grand challenges of robotics]," IEEE Robot. Autom. Mag., vol. 14, no. 1, pp. 43–52, Mar. 2007.
[19] S. Murata and H. Kurokawa, "Self-reconfigurable robots," IEEE Robot. Autom. Mag., vol. 14, no. 1, pp. 71–78, Mar. 2007.
[20] R. R. Murphy, "Marsupial and shape-shifting robots for urban search and rescue," IEEE Intell. Syst., vol. 15, no. 2, pp. 14–19, Mar. 2000.
[21] A. Moreno and M. Regina, "Fundamental Study into Rotor Outwash and Dust Kick-up under Mars-like Conditions," Jan. 2018.
[22] Z. JIE, T. SHUFENG, and Z. YANHE, "Design and implementation of a modular self-reconfigurable robot," High Technol. Lett., vol. 15, no. 3, pp. 227–232, 2009.
[23] B. Salemi, M. Moll, and W. M. Shen, "SUPERBOT: A deployable, multi-functional, and modular self-reconfigurable robotic system," in IEEE International Conference on Intelligent Robots and Systems, 2006, pp. 3636–3641.
[24] Journal of intelligent & robotic systems. Kluwer Academic Publishers.
[25] C.-A. Chen, T. Collins, and W.-M. Shen, "A near-optimal dynamic power sharing scheme for self-reconfigurable modular robots," in 2016 IEEE International Conference on Robotics and Automation (ICRA), 2016, pp. 5183–5188.
[26] G. Jing, T. Tosun, M. Yim, and H. Kress-Gazit, "An End-To-End System for Accomplishing Tasks with Modular Robots," Robot. Sci. Syst. XII, 2016.
[27] J. Davey, N. Kwok, and M. Yim, "Emulating self-reconfigurable robots - design of the SMORES system," in 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2012, pp. 4464–4469.
[28] J. Kim, A. Alspach, and K. Yamane, "Snapbot : a Reconfigurable Legged Robot," pp. 5861–5867, 2017.
[29] S. Ha, J. Kim, and K. Yamane, "Automated Deep Reinforcement Learning Environment for Hardware of a Modular Legged Robot," in 2018 15th International Conference on Ubiquitous Robots (UR), 2018, pp. 348–354.
[30] M. Ning, L. Shao, F. Chen, M. Li, C. Zhang, and Q. Zhang, "Modeling and Analysis of a Modular Multilegged Robot with Improved Fault Tolerance and Environmental Adaptability," Math. Probl. Eng., vol. 2019, pp. 1–17, May 2019.
[31] S. Kalouche, D. Rollinson, and H. Choset, "Modularity for maximum mobility and manipulation: Control of a reconfigurable legged robot with series-elastic actuators," in 2015 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR), 2015, pp. 1–8.
[32] T. P. Cordie et al., "Modular field robot deployment for inspection of dilapidated buildings," J. F. Robot., 2019.
[33] T. Cordie, T. Bandyopadhyay, J. M. Roberts, R. Steindl, R. Dungavell, and K. Greenop, "Enabling rapid field deployments using modular mobility units," in Australasian Conference on Robotics and Automation (ACRA) 2016, 2016.

International Astronautical Federation

100 Avenue de Suffren
75015 Paris, France

Phone: +33 1 45 67 42 60
E-mail: info@iafastro.org
www.iafastro.org

Be part of the conversation @iafastro

Connecting @ll Space People

Chinese Society of Astronautics

No. 8, Fucheng Road, Haidian District
P.O. Box 838
100830 Beijing, China

Phone: 010-68768625
Fax: 010-68768617
E-mail: office_csa@163.com
www.csaspace.org.cn