Architectural Concepts Employing Co-Robot Strategy and Contour Crafting Technologies for Lunar Settlement Infrastructure Development

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A lunar base development strategy that simultaneously employs robots and humans in a safe, effective and economic manner is depicted in this USC School of Architecture and School of Engineering design project done in the Spring of 2012, under the banner of the graduate Moon Studio.

Real time telerobotic systems are proposed as an economically viable strategy for lunar base buildup operations. Co-robots are robotic systems designed and operated in real time using telerobotics, to directly support a variety of complex activities which require human supervision. Use of co-robots will allow real time correction of anomalies, separate and protect humans from a number of risky EVA scenarios, and speed up building processes. The strategy is also applicable for complex construction projects here on Earth, especially in the erection and deployment of critical structures, forward base camps and outposts, where human exposure to building activity is deemed hazardous.

Elements depicted include the design of a permanent lunar landing and lift off pad for repeated crew and cargo/logistics sorties, a transport infrastructure linking the landing pad to the habitat zone, a dust free platform to erect habitat elements, components and configuration of an early phase lunar habitat for six crew members, and a variety of design elements to ameliorate lunar dust effects in the vicinity of this complex. The lunar base complex is seen as the critical foothold for developing a larger permanent settlement. Some architectural concepts developed in the graduate Moon Studio that propose various lunar settlements and activities are depicted.

Eventually, it is the aim of this project to utilize this technology on a large scale here on Earth for complex building projects as well as economic buildup of cities and projects in remote or hazardous regions of the globe using humans primarily in a supervisory role, thereby reducing hard labor, associated fatigue and accidents, while improving overall efficiency of the building process.

Nomenclature

AM	=	Additive Manufacture
BIM	=	Building Information Modeling
CC	=	Contour Crafting
C-TOPS	=	Cabin for Teleoperations

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D-RATS	=	Desert Research and Technology Studies
ELVIS	=	Elevated Lunar Viewing and Information System
EVA	=	Extravehicular Activity
FAIR-DART	=	Filled Aperture InfraRed Telescope-Dual Anamorphic Reflecting Telescope
ISS	=	International Space Station
ISRU	=	In Situ Resource Utilization
LEM	=	Lunar Excursion Module
NAMII	=	National Additive Manufacturing Innovation Institute
NCDMM	=	National Center for Defense Manufacturing and Machining
NRI	=	National Robotics Initiative
RPM	=	Rapid Prototyping and Manufacture

I. Introduction

A new generation of robots, robotic tools and processes are being evolved in an effort to make the US the global leader in the 21st century manufacturing industry. The goal is to vastly improve the productivity, performance, reliability and energy efficiency of the manufacturing industry. Reducing human physical effort(physical labor) while improving safety of the human worker is also a prime concern[The White House 2012].

In Situ Resource Utilization(ISRU) and Contour Crafting(CC) Technology- an offshoot of additive manufacturing(AM) are seen as enabling this 21st century industrial revolution. Some of these approaches to switch from human labor intensive work force to robot intensive platforms are already underway in the heavy machinery and in use widely in the automotive industry.

Crew and robots interacting and operating simultaneously in the same domain, enhancing mission goals and successful project execution is a new area of investigation that is producing highly desirable results. It is called co-robotic activity or human-robot team cooperation strategy.

Space activity offers an arena in which to develop and mature this technology. Space activity is romantic science and engineering for the elders, the Apollo era is considered golden by the last generation, and the next generation think it is “cool to do space”. All of it may be true, but such impressions are not sufficient to make good long-term policy.

Space activity now, as in the past, can be the driving force for rapid societal change, that affect the very fabric of modern civilization, not to mention allow nations to compete and excel peacefully, progressively and economically, across various industries and commercial endeavors. It is in this light and context that the concepts and activities described in this paper are addressed, meant to be understood and assimilated.

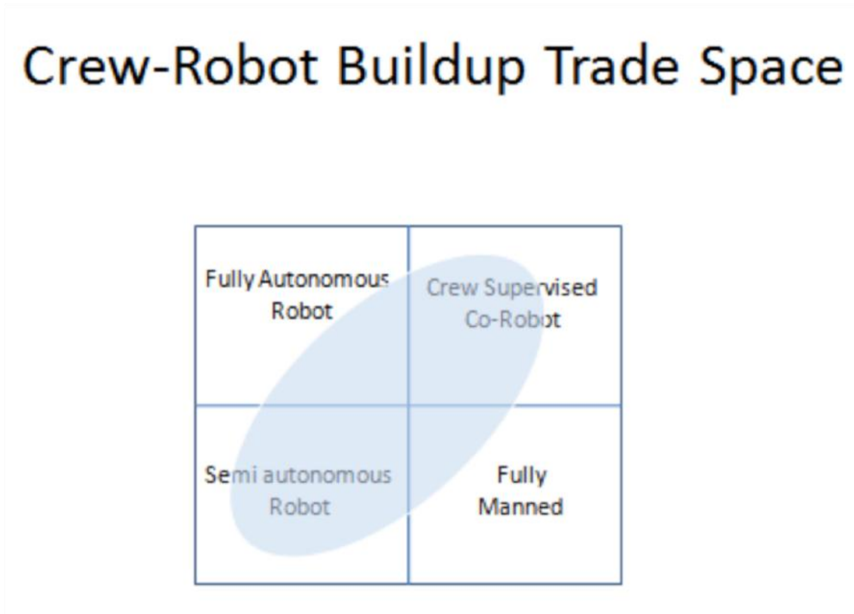


Figure 1. *The co-robotic domain lies between fully manned and fully autonomous buildup philosophy and operations. Co-robotics offers smoother operations during complex extraterrestrial infrastructure buildup.*

A synergetic co-robot and teleoperations strategy for extraterrestrial and hostile environment infrastructure development falls in the category of advanced automation combined with human supervision, that when applied to space activity, may also find routine applications in all walks of life, just as personal computers, and more recently, like smart cell phones , ubiquitous in the modern way of life, across all segments of society, all over the globe.

This human-robot, crew-robot or co-robot trade space is shown in Fig. 1.

Unlike activities requiring command and control at interplanetary distances(it takes an EM signal several minutes to travel from Earth to Mars and back even in the most opportune orbital conjunction geometry), the lunar case offers unique possibilities different from the complete autonomy required for interplanetary guidance, navigation and control.

Robotic assembly of components offers promise for early stage lunar base infrastructure buildup activity including the construction of landing pads, roads and tracks, dust-free platforms as well as for unpressurized shelters protected from particle and thermal radiation and micrometeoritic bombardment.

Contour Crafting(CC) technology, a specialized, patented robotic structure building approach, with roots in the established field of Additive Manufacturing(AM) or Rapid Prototyping and Manufacture(RPM), has been steadily advancing at the University of Southern California for the past decade.[Khoshnevis etal., 2005, 2012]

Earth-based teleoperations may be combined synergetically with robotic CC technology to economically support tasks that can tolerate the 2.77 second round trip time delay introduced by the Earth-Moon distance. [Wheeler etal.,2005]

Lunar surface based teleoperations, also referred to as real-time teleoperations, has been suggested to overcome this time-delay difficulty and well as accommodate certain communication system latencies and may also be necessary for timely feedback and response of certain critical, impromptu tasks that are not time-delay tolerant. [Thangavelu 2008]

Astronauts operating from a lunar lander equipped with a telerobotic cabin may carry out such activities and may also supervise buildup employing CC machines, even allowing direct intervention through EVA to sort out aberrations or anomalies that are quite likely to occur during complex tasks that are part of project execution. A candidate architecture is the Cabin for Teleoperations C-TOPS.[Thangavelu 2008]

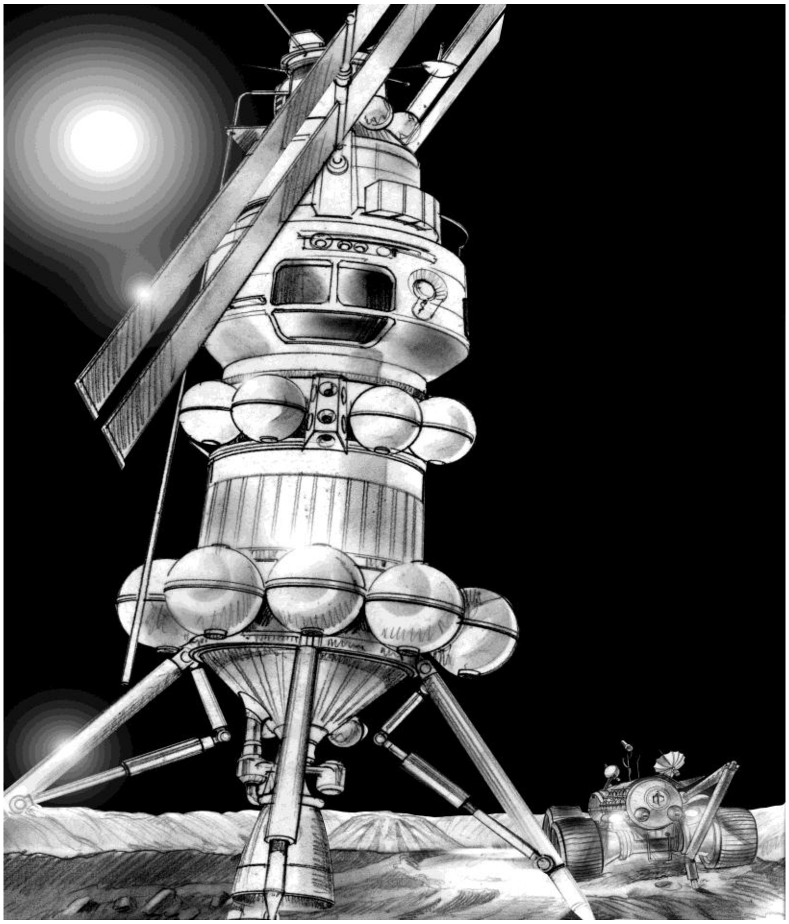


Figure 2. *The Cabin for Teleoperations (C-TOPS) would allow crew on the lunar lander to supervise robots in visual/EVA proximity to execute complex tasks employing real time telerobotics. If and when anomalies occur, crew can correct them quickly in EVA. So, EVA is used only for correcting anomalies during robotic operations. C-TOPS is an example of a co-robotic architecture.*

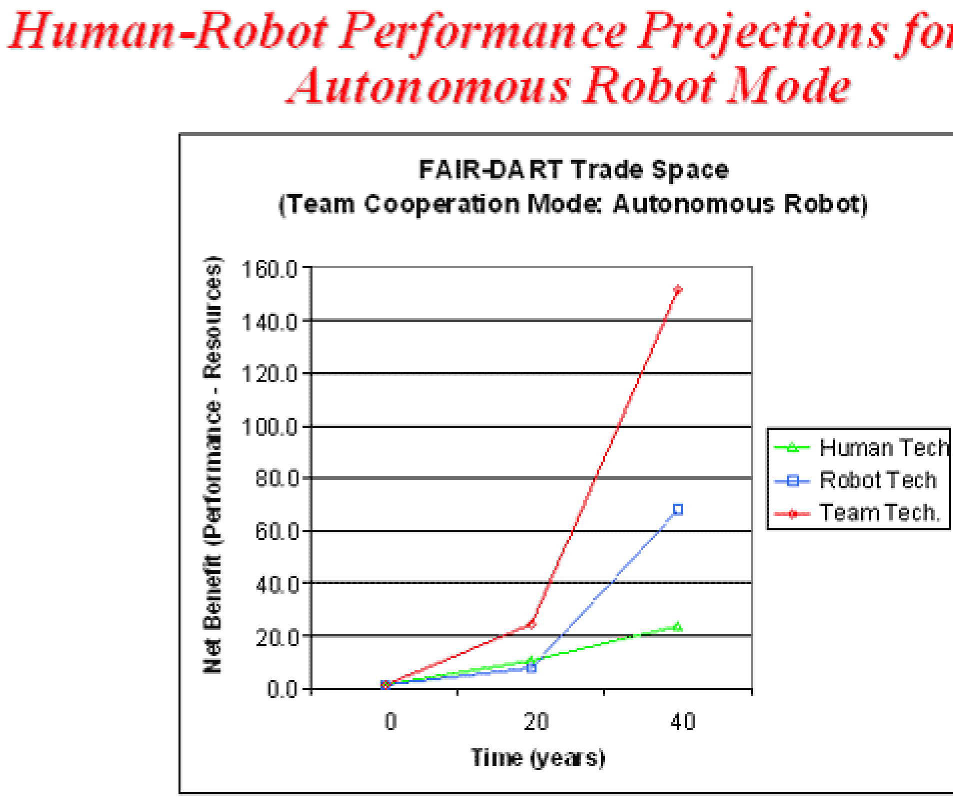
Robots designed for specific functions also tend to be very quick and efficient in executing them, thereby compressing time schedules for project execution. They are very consistent in accomplishing assigned tasks and do not need recuperation periods between shifts. Regular maintenance is required but can be implemented even during work shifts. These factors make them attractive on the factory floor, compared to human workers.

The risk associated with fully robotic lunar assembly is the potential for schedule slippage or mission failure due to robot system malfunction or associated anomalies that cannot be resolved by Earth based teleoperations as shown in several studies like the FAIR-DART[Stephens 2002] and the robotic Hubble Space Telescope mission[NASA 2004, SSB NRC 2005]. Adequate redundancy has been suggested to overcome this strategic deficiency and recent advances in robotics will overcome many of these obstacles as newer generations of robotic hardware and software arrive.

But for near term applications, real-time teleoperations by lunar surface based crew allows to correct this problem. However, when crew are introduced into the loop, safety and other critical mission constraints such as life support duration need to be taken into consideration[Thangavelu 2010].

Robots tend to perform as well or better than humans when the tasks and conditions can be reliably predicted. Humans are better-equipped to deal with the unexpected or abnormal[Rodriguez and Weisbin 2003] Human operators tend to fatigue rapidly when assigned repetitive tasks that robots carry out very efficiently. Therefore it is possible to carefully plan mission tasks and allocate those tasks that are best done by robots quickly and efficiently and assign others requiring impromptu feedback and dexterity to humans, thereby vastly improving mission performance.[Rodriguez etal., 2002, H.Hua etal., 2008, Elfesetal., 2008]

It is possible to synergistically combine the telerobotic and real-time human supervision approach using the co-robot strategy. The co-robot or the robotic assistant is designed specifically to complement the astronaut team capabilities to carry out complex tasks, adopting an optimal, flexible, man-machine synergy model.[See Figure 3: Human-Robot Performance Projections Team Cooperation Mode]



Rodriguez, et al, Human-Robot Performance Analysis Methods, JPL Report, Aug. 6, 2002.

Figure *3.Co-robotics, or team cooperation strategy offers better efficiencies when proper schedule programming routines are employed. Team cooperation between robots and crew also allows to accommodate impromptu changes during project execution as well as quick anomaly resolution, resulting in higher efficiencies.*

Co-robots can help save time and resources while accomplishing mission tasks, sometimes requiring unrehearsed, impromptu or on-the-spot activities to correct deviations from routine and schedule. [Elfes etal., 2008]

A series of new initiatives by the current administration[White House 2012], a recent report about US Robotics(Christensen 2009) followed by an RFP called the National Robotics Initiative(NRI 2012) highlighted the importance of the co-robot strategy in the rapidly developing current context.

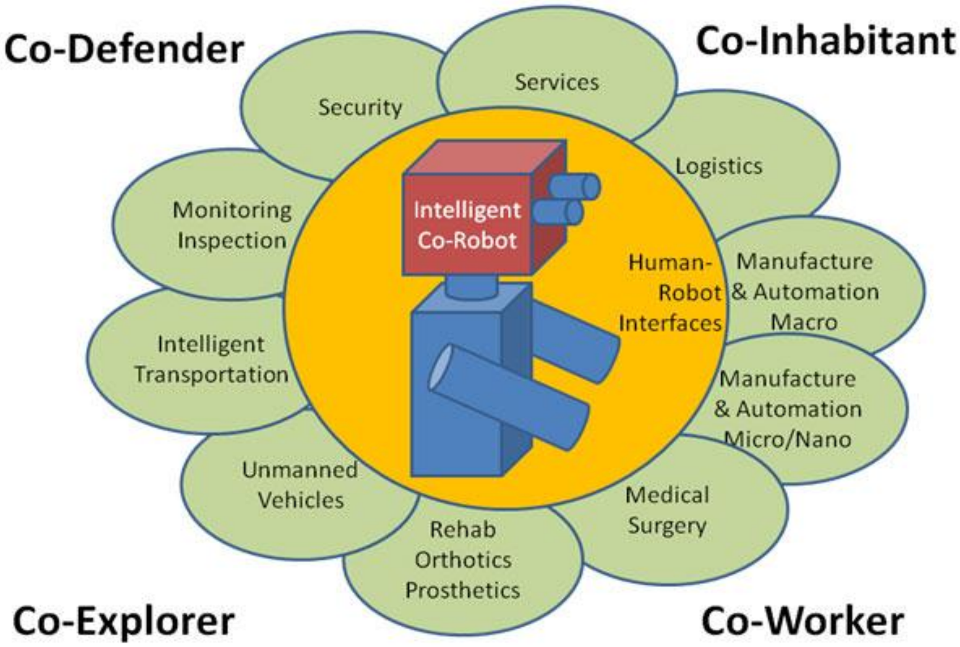


Figure 4a. *A co-robot directly interacts with humans, using real time feedback loops to assess situational awareness and define its operation. [Credit NRI 2011]*

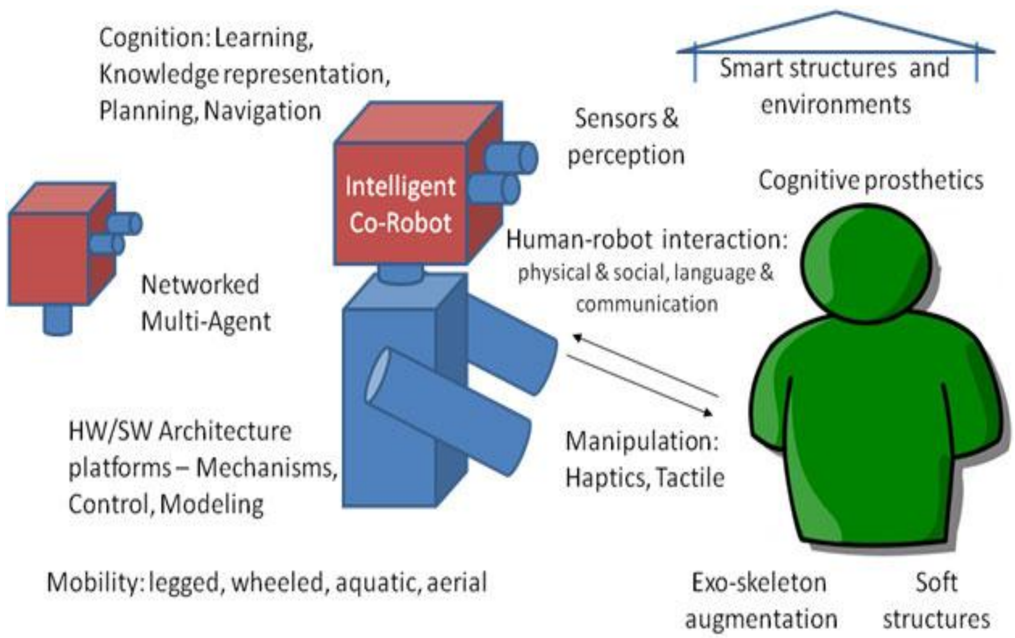


Figure 4b. *A co-robot directly interacts with humans, using real time commands and feedback loops to assess situational awareness and define tasks for operation and project execution[Credit NRI 2011]*

A co-robotic agent directly couples with humans to execute complex tasks, while removing humans from direct physical involvement on site.[Fig 4a,b] Autonomy is present a various levels within the command and control chain hierarchy, but the intent and goal execution is controlled by the human operator. Prime examples include the highly effective drones used in terrorism suppression, telemedicine surgery, advanced flight controls in aircraft such as the Boeing 787 and fighter jets, as well as certain controls in automobiles being routinely used today.

To be clear, this approach is very different from the the operations of a fully autonomous system like that executed by the MSL/EDL[NASA JPL 2012] or the proposed demonstration of the NGC X-47B system aircraft carrier landing, where no human input is involved during the execution phase of the mission.[Dillow 2012]

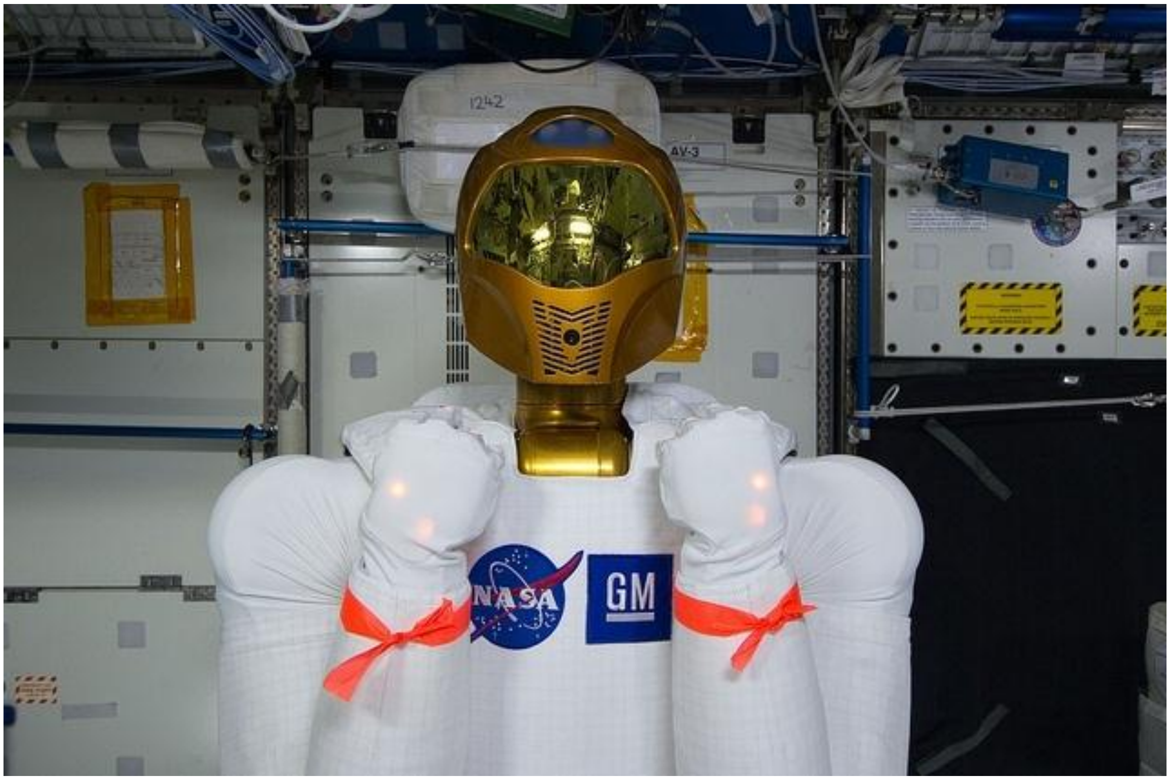


Figure 4. *Robonaut 2 deployed on the ISS before arm activation*

The co-robot, like the Robonaut 2[Fig. 4] now deployed and in service on the International Space Station(ISS), employs neural network algorithms to continually learn and hone tasks to assist the astronaut crew to safely and quickly accomplish mission tasks.[Fong etal, 2002, 2010]

Of course, the proposed co-robot and teleoperations approach offers much promise for advance base deployment in hostile environments like those posed on the Martian satellites Phobos and Deimos to facilitate co-robotic base buildup activity on the Martian surface[Hopkins and Pratt 2011] and here on Earth as well, opening up new opportunities for the design and building of complex urban development projects.

II. NASA Robot Scaffolds of Interest for Grafting Co-Robotic CC Building System

The current Contouring Crafting system at USC has matured as a capable and versatile terrestrial automated building system. A working unit has been tested at NASA Marshall Spaceflight Center and several advanced versions are in development or under study at USC. Research underway is also looking for ways to adapt CC technology quickly and efficiently to support NASA missions.

One way to achieve this goal is to graft the co-robot philosophy with CC technology to existing NASA robots that are being field tested and those which show promise for grafting CC technology.

There are a few important physical and operational parameters to pay attention to while selecting the appropriate robotic scaffold for space based CC technology. They include the ability of the scaffold to:

1. Be sturdy(while locked In position) under variety of terrain conditions
2. Be sturdy and still while the CC system is operating
3. Be operable in lunar extreme environment
4. Be able to carry and exchange variety of end effectors
5. Last but not the least, be co-robot activity friendly

Several NASA robots being field tested need to be investigated and empirically demonstrated in order to reliably ascertain which one is best suited for the CC building system.

Proposed CC scaffolds include systems being tested at NASA D-RATS depicted below, Figures :5 a-h(5h variations are not depicted in this document)

Figure 5a. *The NASA/GM lunar pressurized rover with trailer bed*

Figure 5b.*The unpressurized Chariot Chassis with appropriate CC systems*

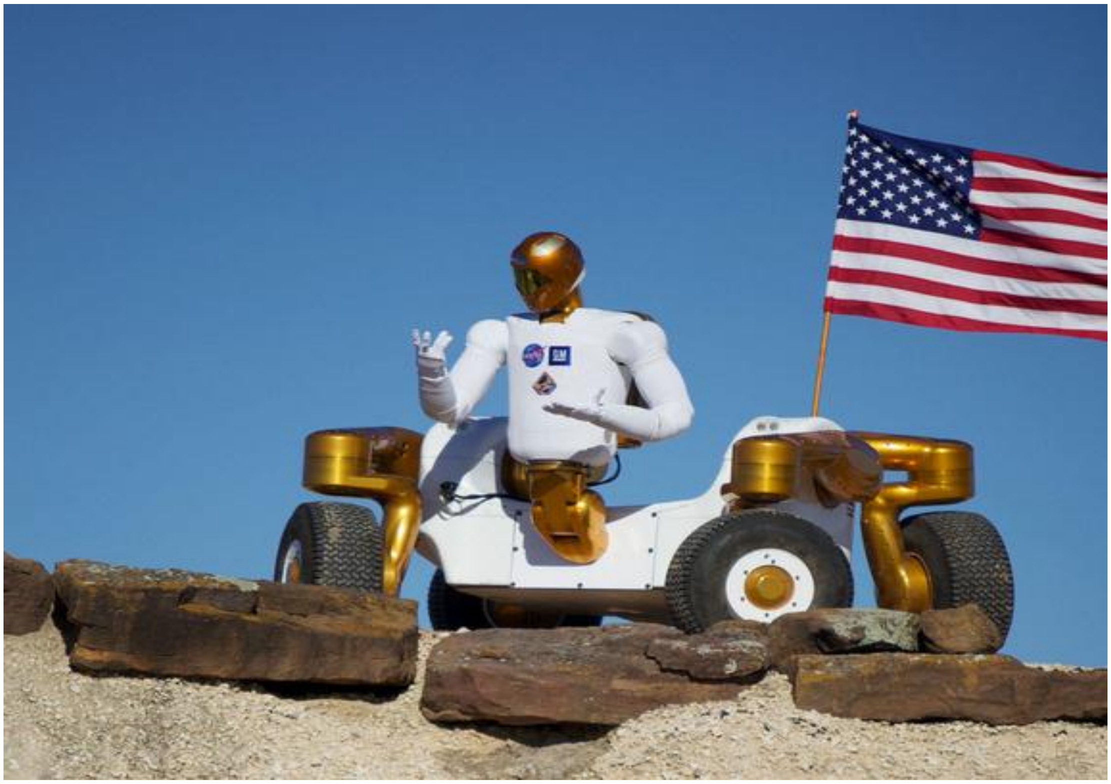


Figure 5c. *The small robotic Centaur*

Figure 5d. *The ATHLETE chassis*

Figure 5e. *The NASA light weight Dorsey Crane*

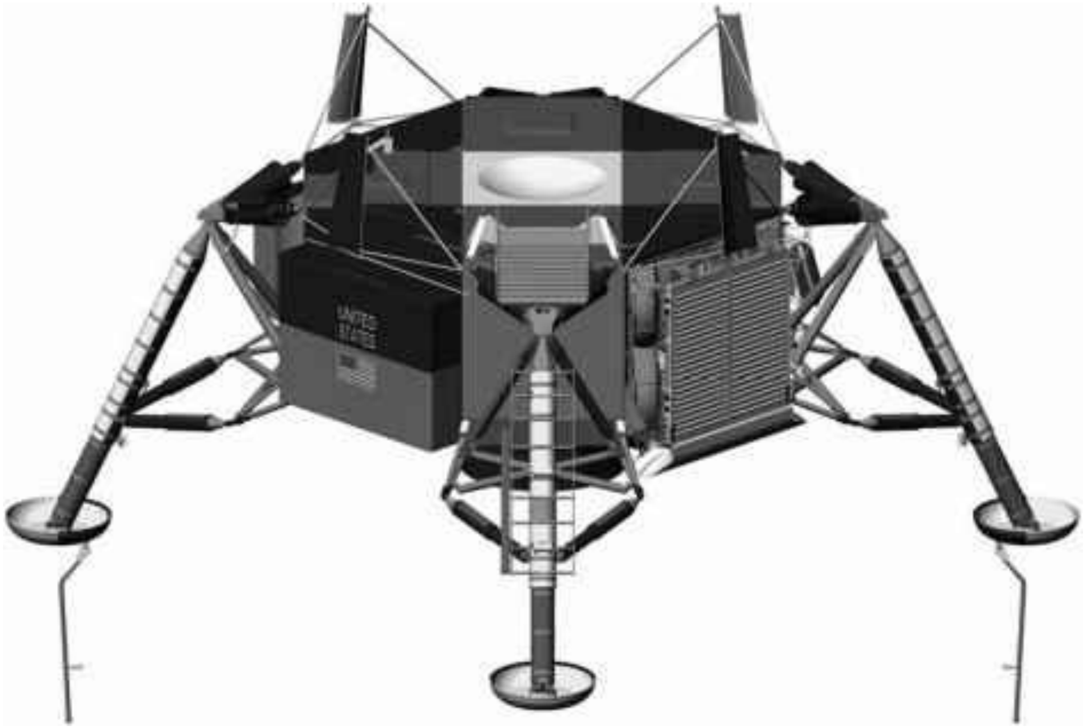


Figure 5f. *The used Descent Stage of the lunar lander*

Figure 5g. *Classic Contour Crafting gantry building a terrestrial multistorey structure*
Figure 5h. *Hybrid options using all or some of the above in concert.(not depicted)*

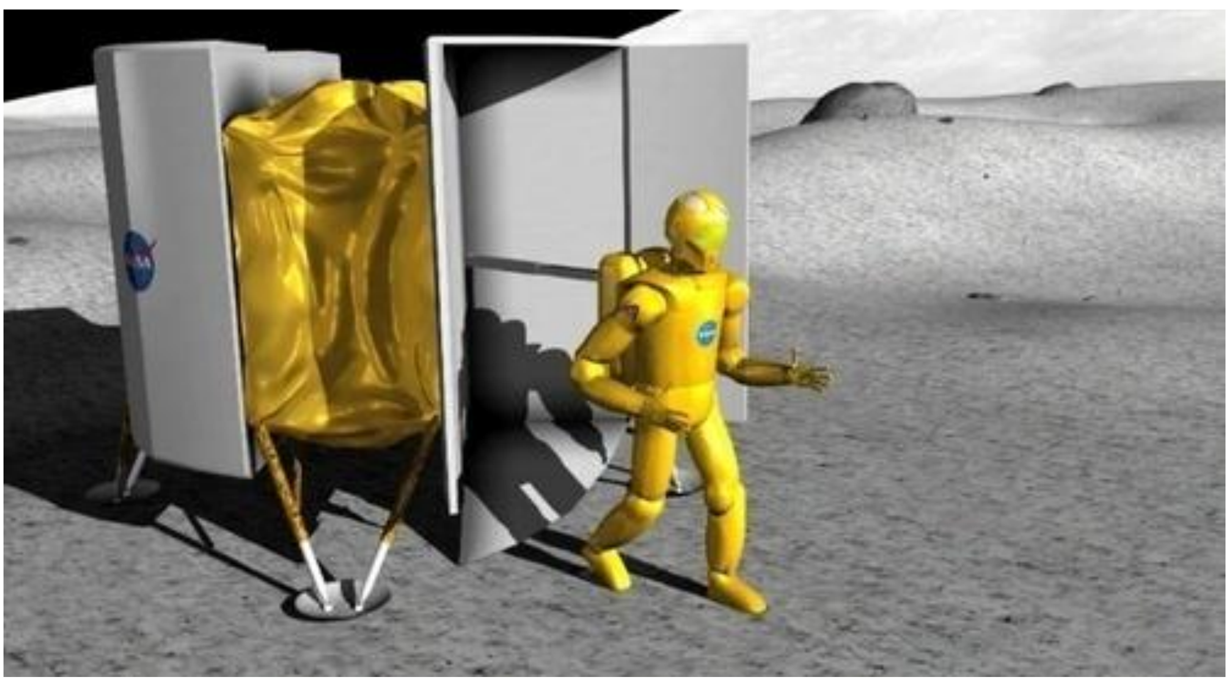


Figure 6. *NASA's Project M would use a co-robot strategy, employing anthropomorphic robots in complex lunar infrastructure development tasks.*

The principal task to be conducted on CC systems grafted to above NASA robotic scaffolds is to test which of these systems operate the best under co-robot environment in which they are assisted by astronauts and real time telerobotics.

NASA's Project M(see Figure 6) would employ a co-robot strategy for doing complex infrastructure development tasks.[Ondler 2010]

III. USC Projects employing CC technology and Co-robotics

Projects employing these NASA assets along with CC technology and co-robotic strategy are depicted in figures 7-9. They include hangars, roads and landing pads and associated elements for an accelerated lunar settlement infrastructure establishment.

Of course, it is important to note that the CC system is an evolved system that is also versatile. Besides contour crafting, it can also be programmed to carry out a variety of tasks designed and reserved for other robotic systems including fabricating building components like tiles and beams, blocks, bricks and sheets that may then be positioned accordingly. The system may also be used to pour slurries, deposit powders, dry pack aggregates and rough hewn regolith rocks, not to mention CC system components could also engage in precursory site developments like ground clearing, trenching, leveling and large scale visual marking/zoning for lunar landing aids.[Whittaker 2009, Simon&Sacksteder 2007]

An interdisciplinary team comprising of USC Engineering and USC Architecture faculty and graduate students are currently studying various aspects such as:

1. List tasks and develop metrics for lunar CC system
2. Compare and contrast different configurations using NASA robotic and developing co-robotic scaffolds and hooks and scars for CC
3. Evaluate the merits and limitations of each configuration
4. Select the most efficient and reliable CC system and co-robotic scaffolds for extraterrestrial and harsh Earth environment application and
5. Suggest variations for different environments ranging from the lunar case to the Mars and the asteroid case, with valuable Earth applications also in mind.

Figure 7. *A Lunar CC System building an unpressurized storage hangar. A beneficiation plant that produces various feedstock from lunar regolith may be seen in the background. The lunar electric rover with a trailer cart would carry the feedstock in sorties from the plant to replenish the CC machine.(credit C.Wingfield, B.Farahi)*

Figure 8. *Lunar hangars and roads being built using CC technology and NASA rovers and other assets adapted to CC system.(credit C.Wingfield, B.Farahi)*

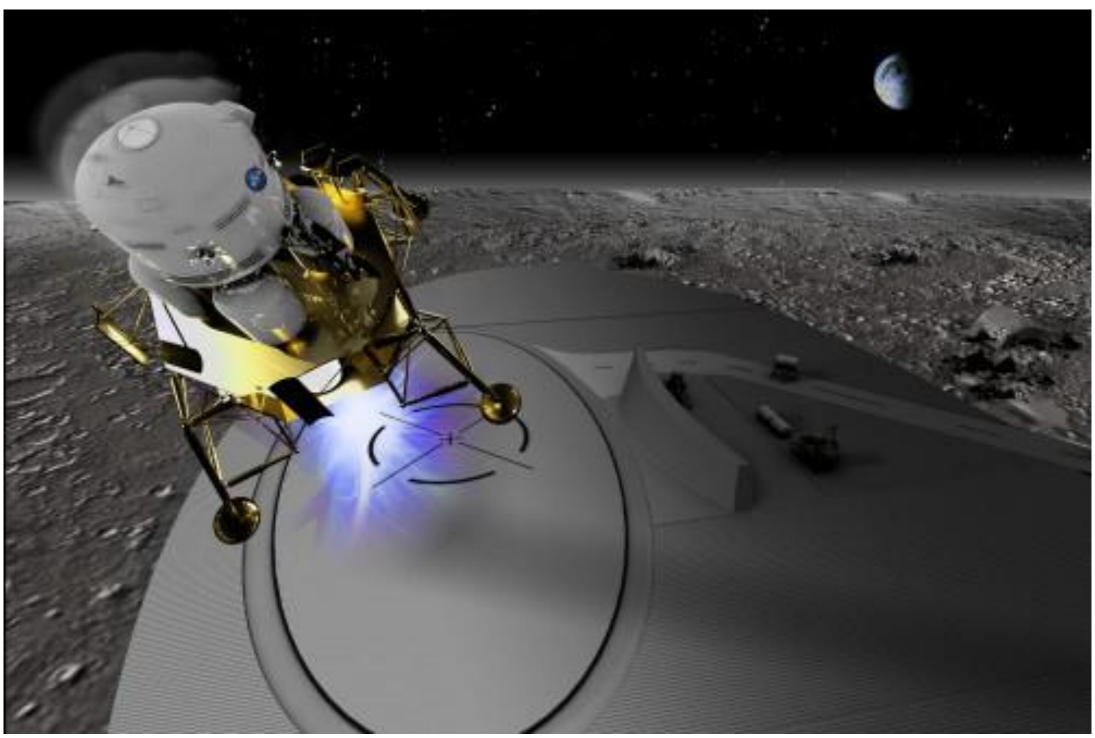


Figure 9. *A lunar landing pad, fuel depot and blast wall complex at the polar lunar regions may be built using CC technology combined with co-robotics.(credit C.Wingfield, B.Farahi)*

IV. Some Lunar Projects That Could Employ the Co-Robotic Strategy for Buildup

In the Spring 2012 Graduate Moon Studio conducted by the USC School of Architecture, students were exposed to the current topics in lunar exploration and extraterrestrial habitat design. Following several topical lectures ranging from NASA's long range plans and human factors to lunar agriculture prospects and space architecture, after extensive background research, they produced alternative conceptual designs for lunar development. Some of the designs proposed, which could be realized using CC and co-robotics are depicted here.

A. ELVIS: Elevated Lunar Viewing and Information System

The Spring 2012 Arch605 Graduate Moon Studio offered by the USC School of Architecture was a design program based on current academic research involving the future of human lunar activity. The class project was to research the moon's hostile environment and develop a proposal for lunar return that we thought could eventually become viable, with commerce and self sustainability playing a leading role. This project examined possibilities of lunar tourism in the near term.

Precedents, particularly one by the disbanded BlastOff Corp. of Pasadena, CA., that looked at landing small robotic craft at the Apollo 11 site to beam back images of the Eagle and first foot prints were studied. Current Google X prize ideas to return small robotic craft to the Moon were explored. ELVIS concept differs from them by catering directly to commercial lunar tourism. The joint Space Adventures / Russian Space Agency concept to send people into lunar orbit for $150M per ticket is baselined, ELVIS project is expected to cost more because of all the surface activities that it entails.

The basic concept of this proposal is to create a lunar touring system that will allow visitors to be on site at some of the most exciting visual landmarks(many of them observable from Earth), geological formations, as well as historically relevant sites in our solar system. Sites include Apollo, Surveyor, Luna and even some spectacular crash sites of robotic spacecraft.

A highlight of the program provides an on-site high resolution holographic projection (video with audio) of USC alumnus Neil Armstrong setting his foot on the moon during the climax of the historic Apollo 11. In this way, the tourist would be able to "relive" the historical moment when humanity first set foot on another celestial body, considered by many historians to be the pinnacle of human achievement in the 20th century.E.L.V.I.S. (Elevated Lunar Viewing and Information System) is a masted disc structure that covers an accommodation and habitat tunnel structure when not in use, but can elevate to help visitors get a better vantage point and more knowledge of the site they are about to explore. For sites that are too difficult to see on foot, or have restrictions placed on them like Apollo 11, a gondola suspended from ELVIS would allow tourists to get a closer look without disturbing the site.

Figures 10-17 explain the architectural concept of the Elevated Lunar Viewing and Information System.

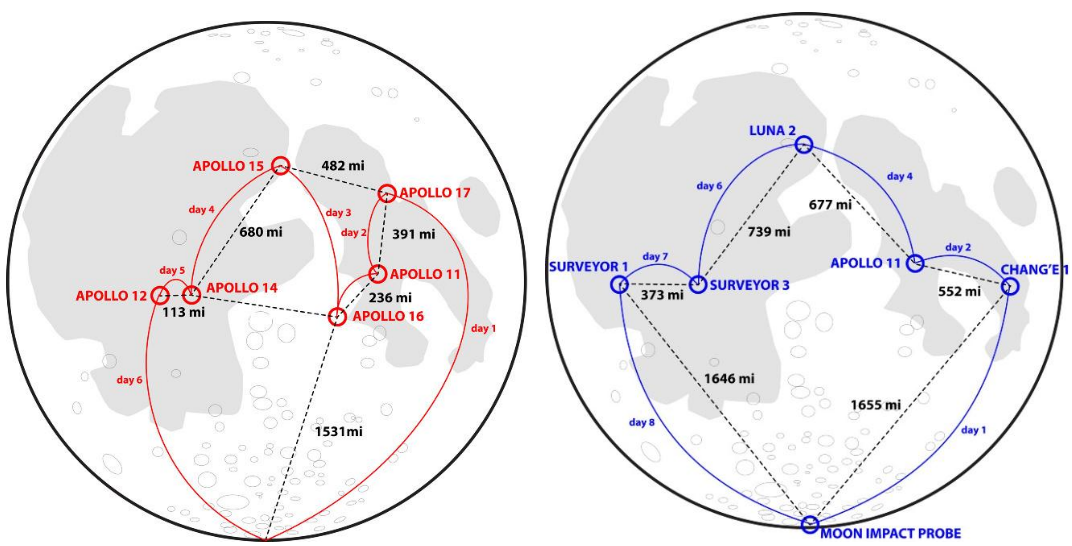
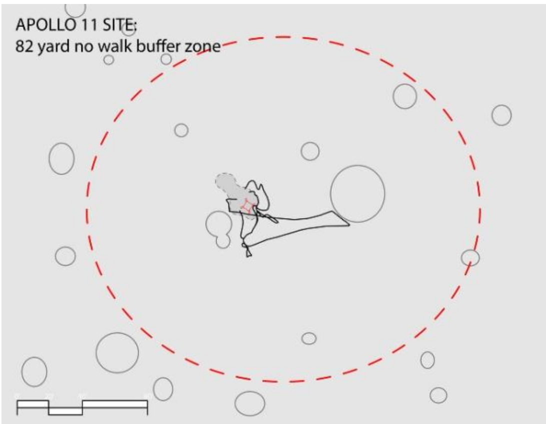


Figure 10. *The ELVIS tour of historic lunar sites is timed to take advantage of the diurnal motion of the lunar terminator(credit F.Sharpe)*



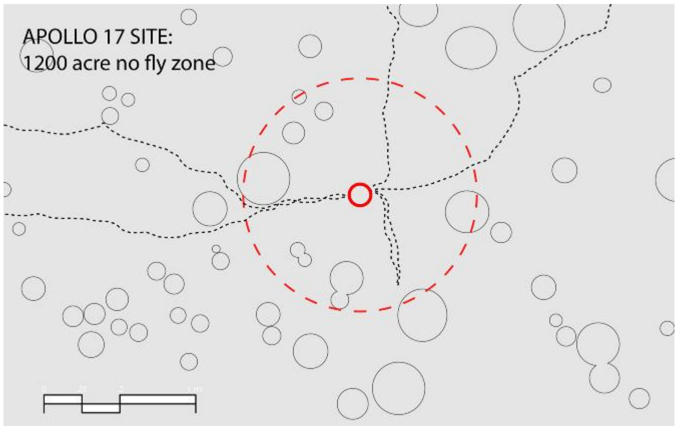
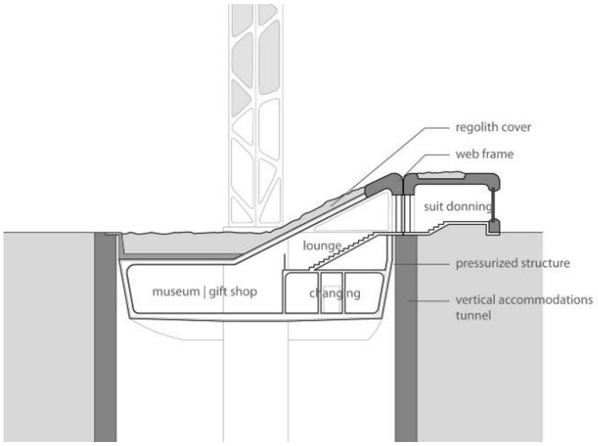


Figure 11. *Program had to solve the "no fly' buffer zone problem imposed by NASA and US government: How to routinely access the site for tourism without disturbing it ?(credit F.Sharpe)*



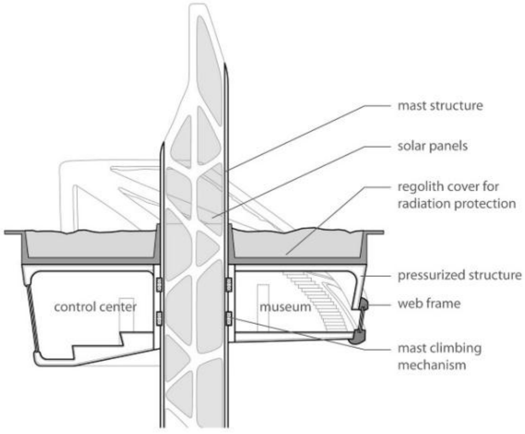


Figure 12. *Sections through ELVIS shows the sliding habitat torus wrapped around the tower mast that supports the cable car operation.(credit F.Sharpe)*

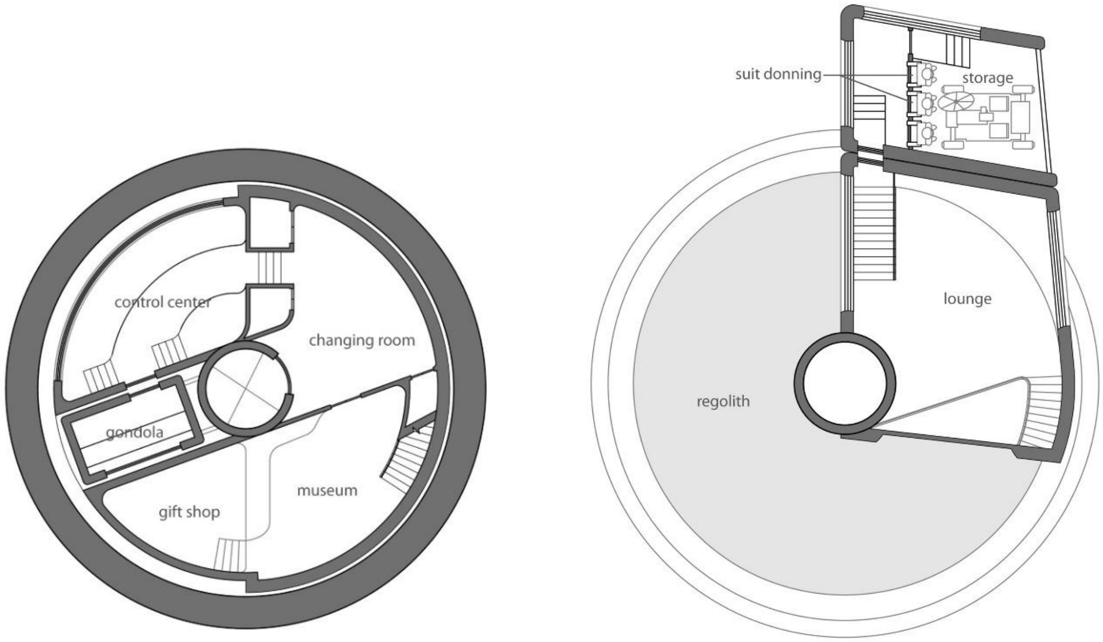


Figure 13. *Plans for ELVIS floor layout shows spatial functions. They include a control room, a spacesuit donning and doffing room adjacent to gondola boarding room, a gift shop and a museum. On the ground level is a lounge and a parking garage for rovers as well as an airlock.(credit F.Sharpe)*

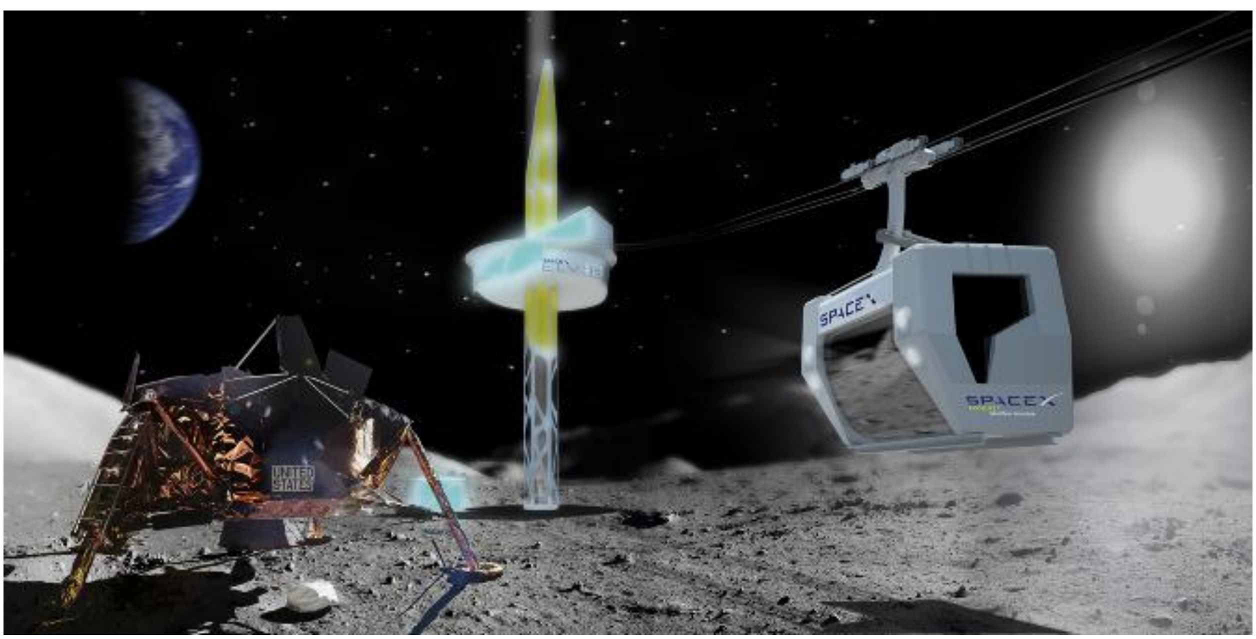


Figure 14. *A cable car system with holographic projection system is proposed to access "don't disturb" sites in order to "relive" the historic Apollo 11 lunar landing.(credit F.Sharpe)*

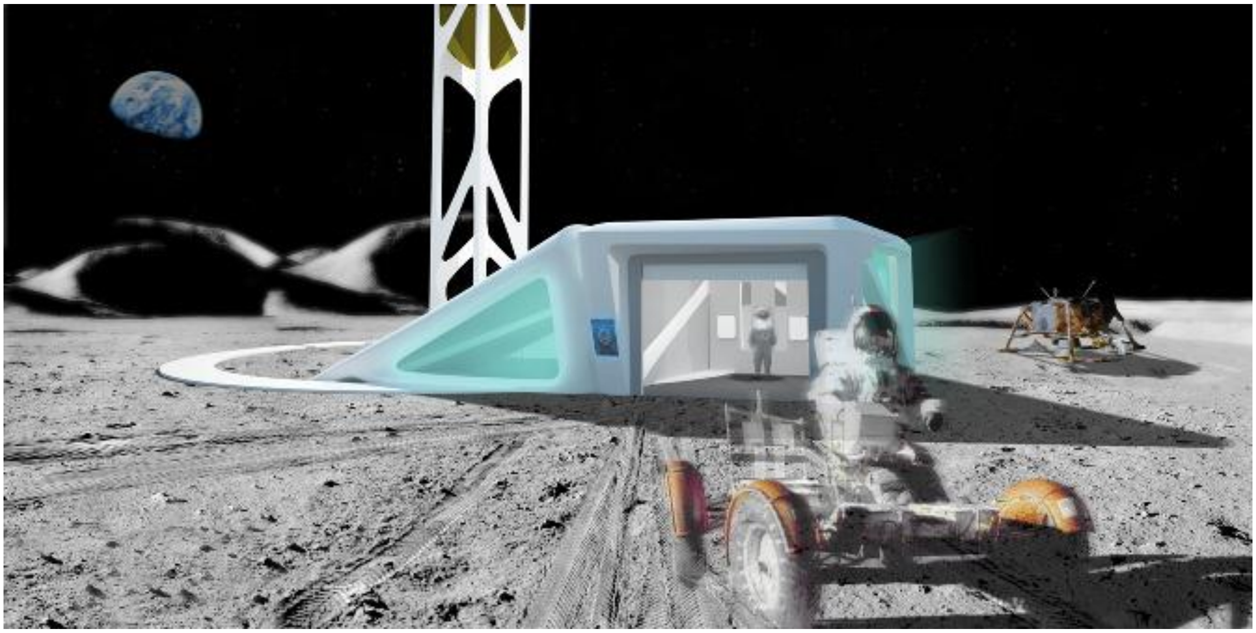


Figure 15. *Airlock access on ELVIS allows tourists to take the lunar rover for a spin.(credit F.Sharpe)*

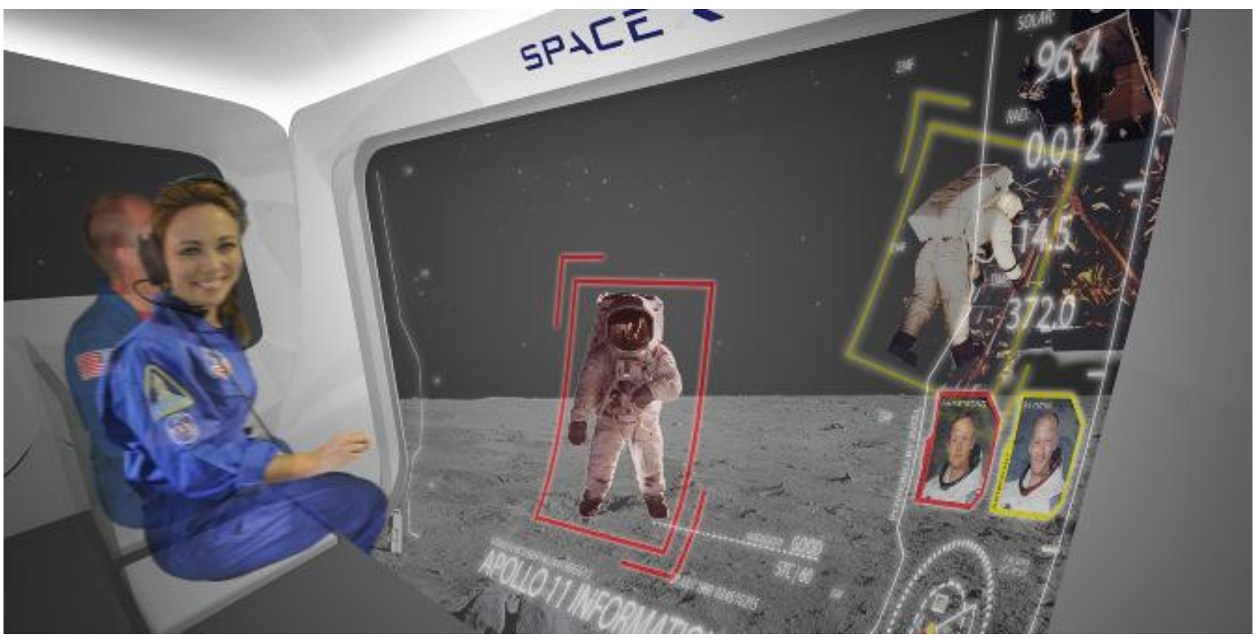


Figure 16. *Crew stationed at ELVIS take visitors on an in-depth information and technology tour, aided by holographic projection of historic events.(credit F.Sharpe)*

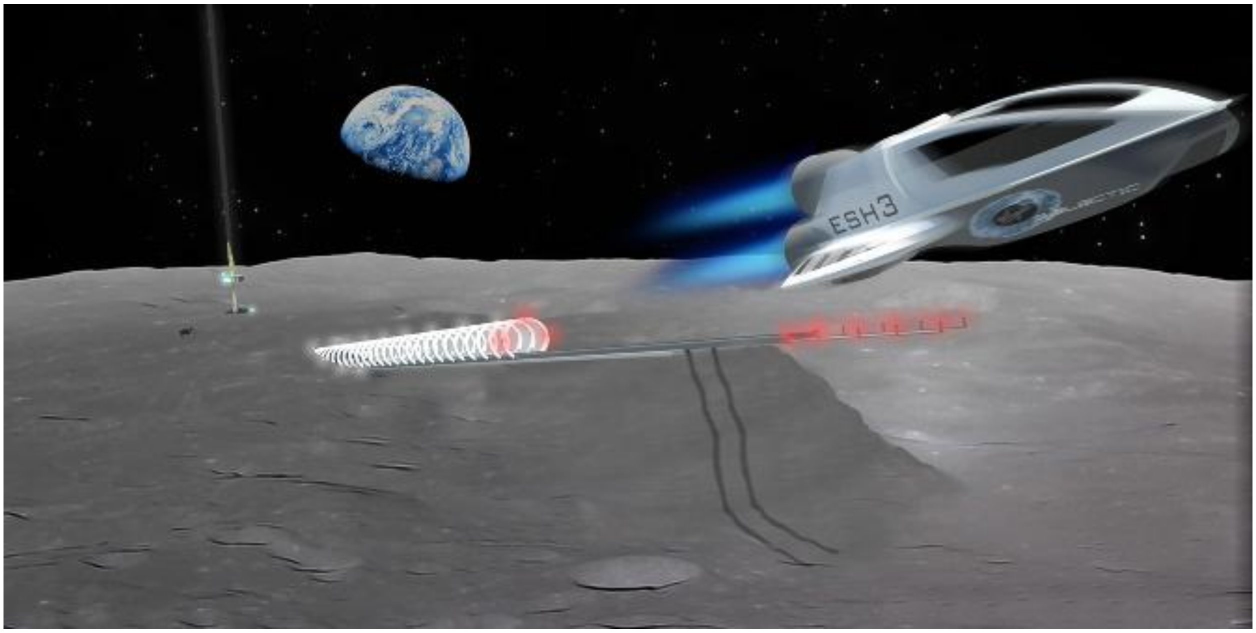


Figure 17. *A hybrid technology based propulsion system(chemical / electromagnetic rail gun) transports the tourists from site to site in synchrony with the lunar terminator. The entire tour is expected to last 14 Earth days, and the tourists return to the International Space Station from where they are ferried back to Earth, and to their respective national destinations.(credit F.Sharpe)*

B. Digital, Biomimetic Architectures for Lunar Development

Architects continue to derive tremendous inspiration for their concepts and designs from nature. The architectural community is also very engaged in building performance, and tools like the Building Information Modeling(BIM) have been developed to improve it(Eastman etal., 2008). Material performance and energy conservation are foremost on architects minds while they create new and innovative buildings. These traits are shared by the astronautical designer as well.

Smart buildings now carefully monitor and tweak their own environments for maximum efficiency and energy conservation round-the-clock, taking into account the time of day, occupancy loads, anomalous weather conditions, and even actively respond to lateral and dynamic loads imposed by natural agents such as rain, sleet and snow as well as accommodate rapid adjustments to damp oscillations caused by resonant vibrations in super tall structures. Tall buildings even actively respond to compensate for movement from random swaying due to wind or lateral movement caused by earthquake tremors. Building technologies now routinely offer surveillance, and autonomously activate fire control and other safety systems in the event of an emergency.

Some of the current fascination with science and technology within the civil architectural community include form-finding employing analogies from binary computation, digital fabrication and 3D printing, emergence and self organized criticality arising from complexity(Simon 1962, Bak 1996), genetic algorithms and morphogenetically evolved shapes and forms, informed by cellular automata and self-reproducing systems that follow the seminal works of mathematicians like Alan Turing and John von Neumann, and pioneering digital DNA biologists Craig Venter and George Church among others.

The following conceptual designs in figures 18-20 makes use of these philosophies to generate cellular habitat units that are proposed to autonomously create complex dwellings on the lunar surface using co-robots and CC technology.

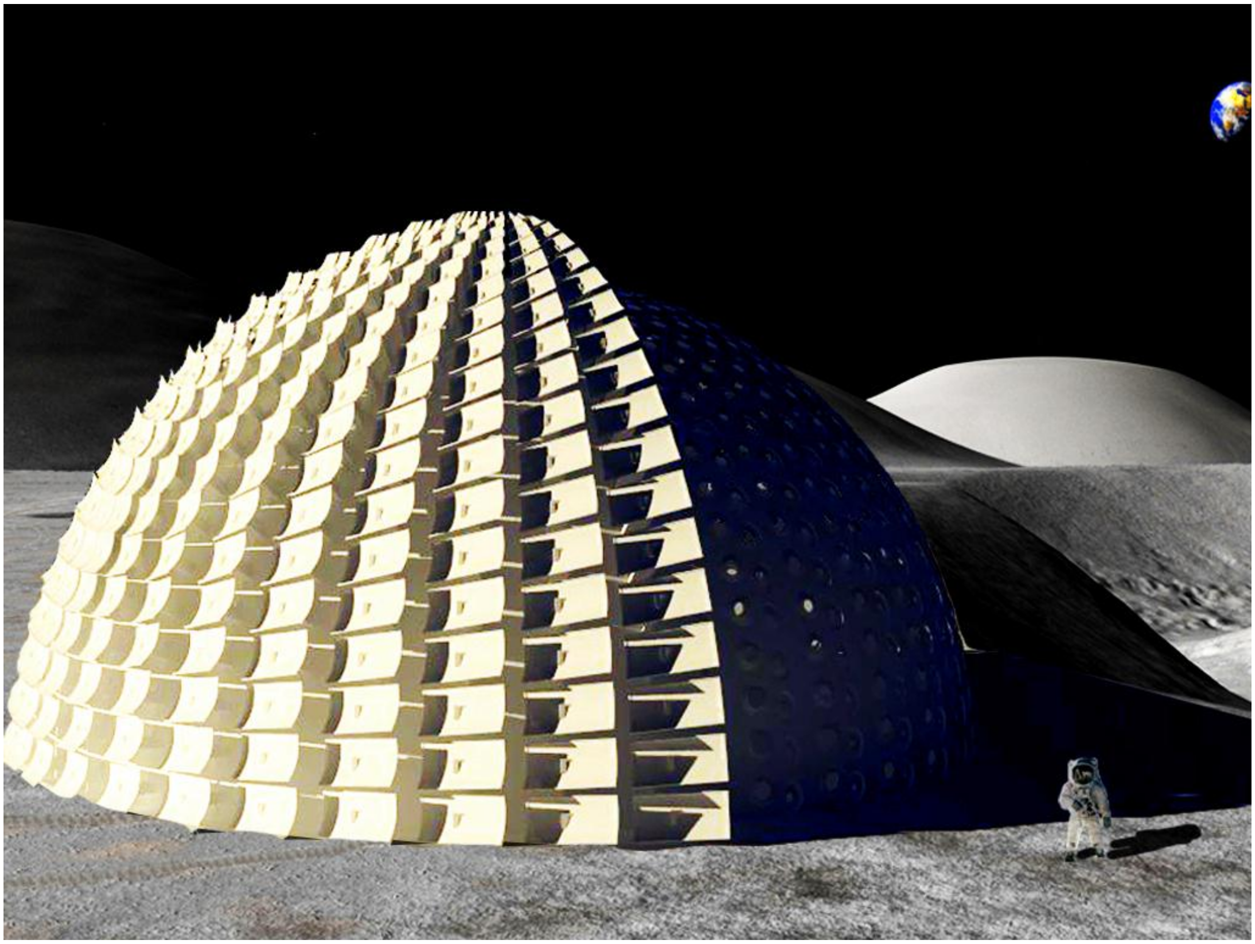


Figure 18a-c. *A south polar lunar habitat that tracks the sun around the polar horizon and employs lunar water to maintain optimum interior temperature also has modular micrometeoritic shielding built into it, using ISRU and CC technology employing co-robot strategy.(credit K.Dolat)*

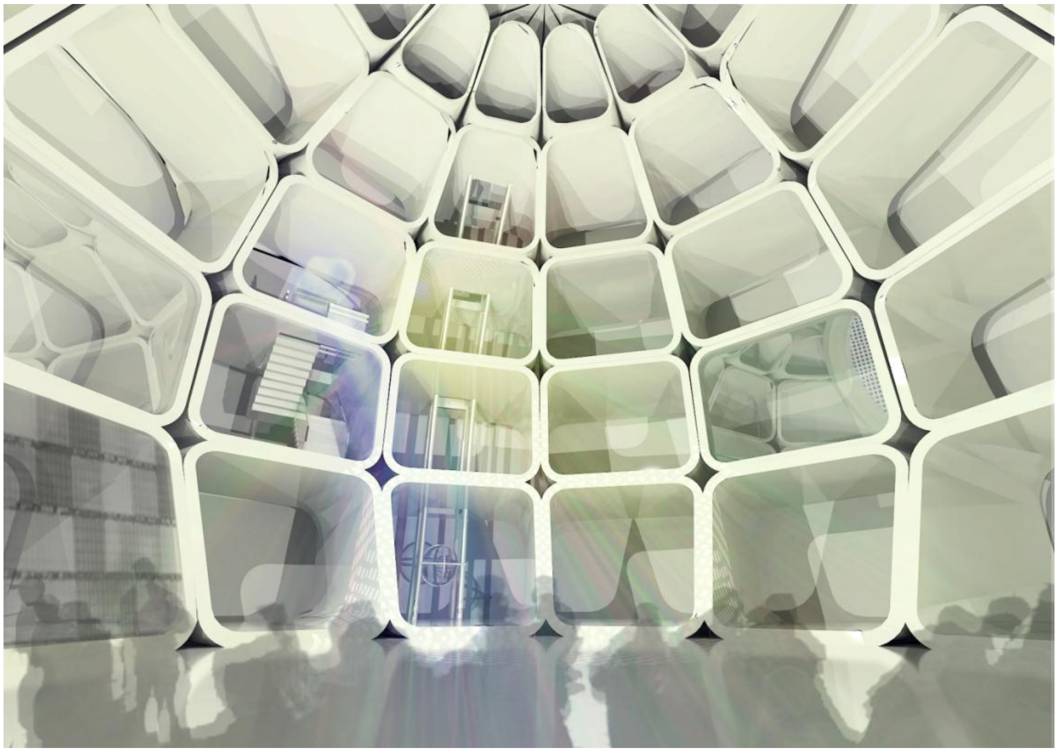


Figure 18b. *The interior of the sun tracking, water-ice shielded lunar polar habitation(credit K.Dolat)*

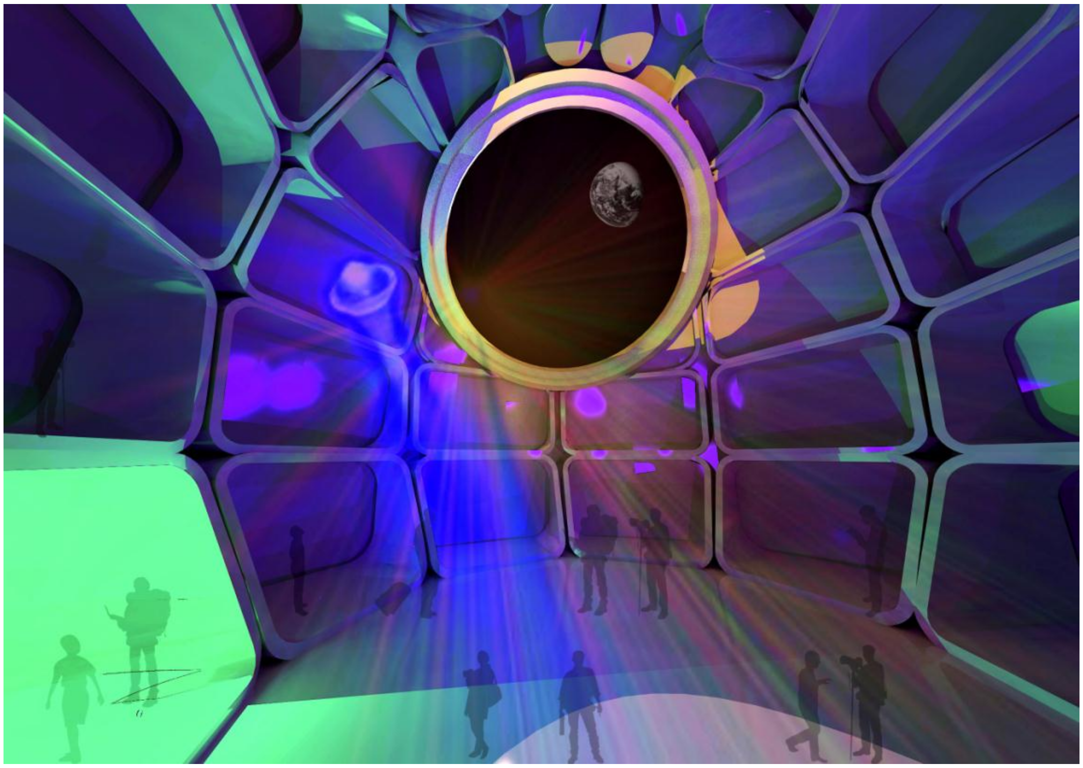


Figure 18c. *A large radiation shielded window allows views of the polar horizon.(credit K.Dolat)*

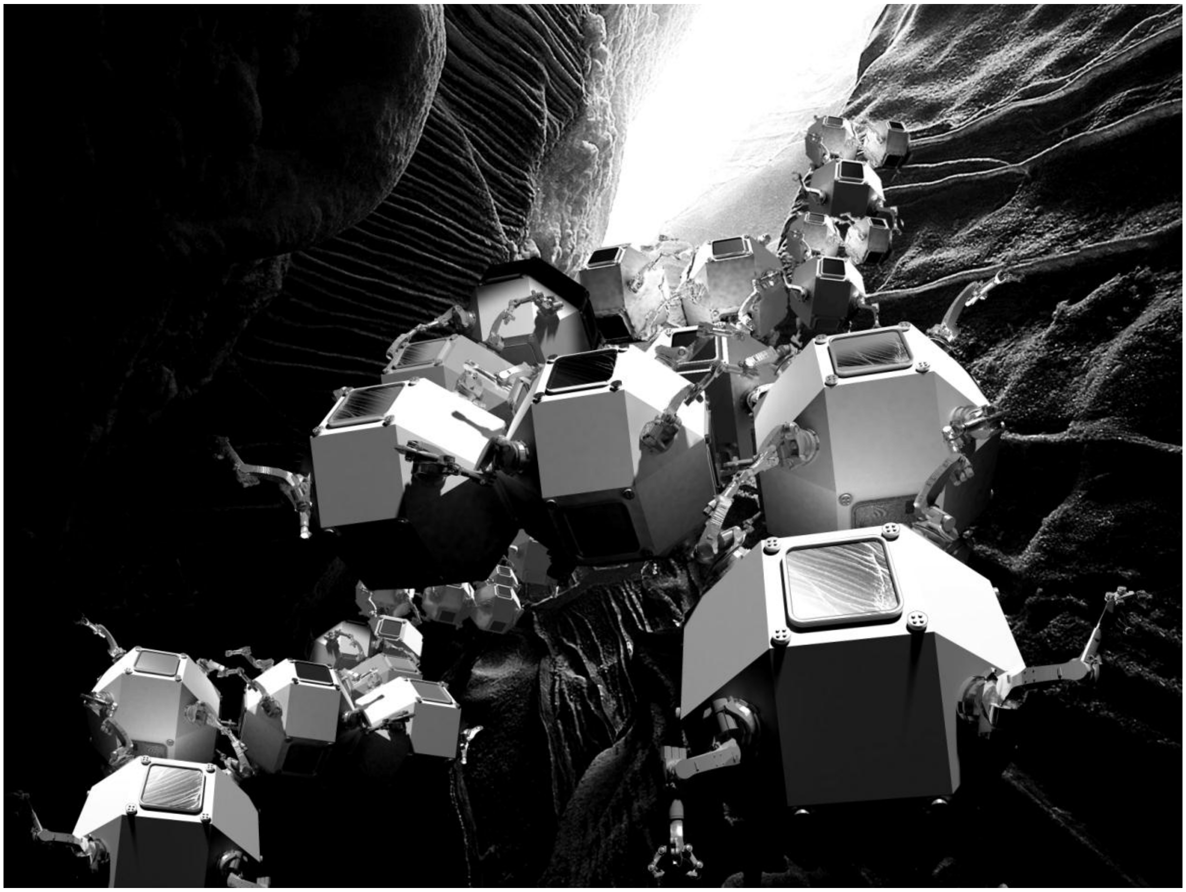


Fig 19a-e. *Cellular, modular, mobile habitat units may be able to coordinate movement, find suitable sites for permanent settlements, and align themselves to form complex habitation structures, and evolve over time as needs and utilities change.(credit B.Farahi)*

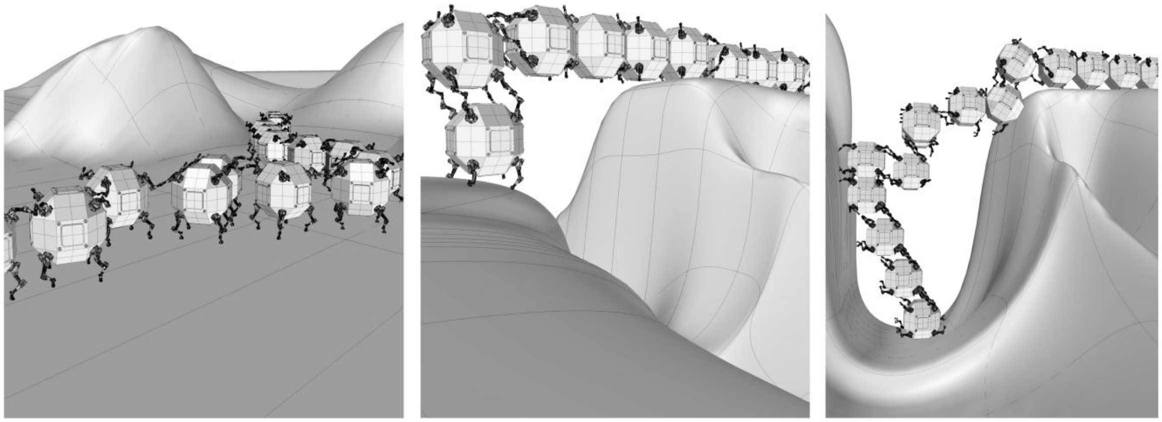


Figure 19b. *shows how the cellular, modular habitat components are able to move, mitigate a variety of terrains, and congregate to form complex habitats on the lunar surface.(credit B.Farahi)*

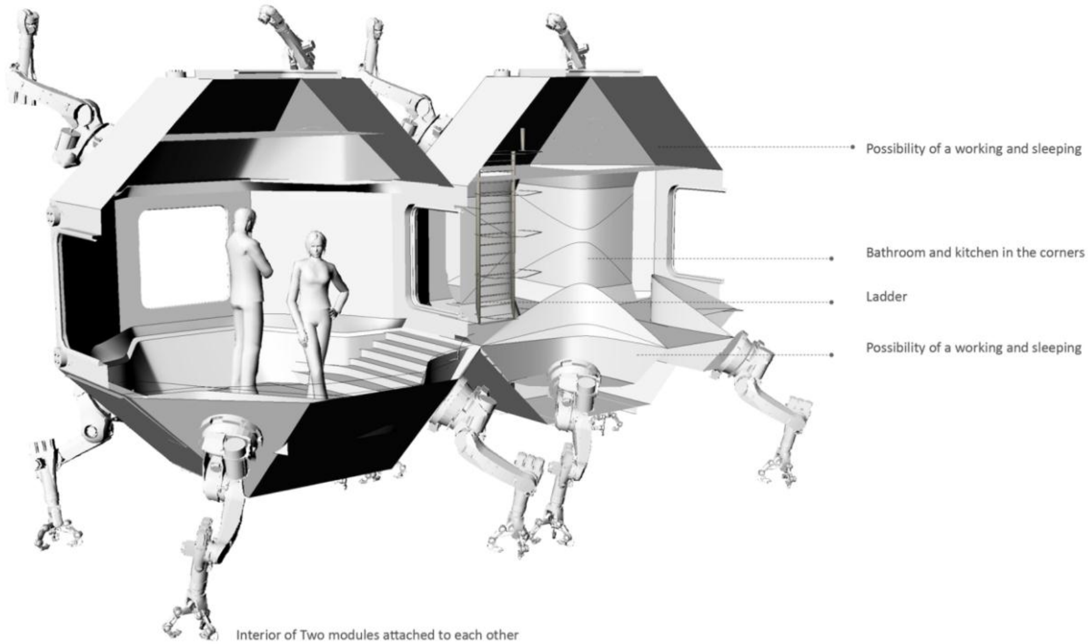


Figure 19c. *shows a section of the cellular, modular mobile habitat.(credit B.Farahi)*

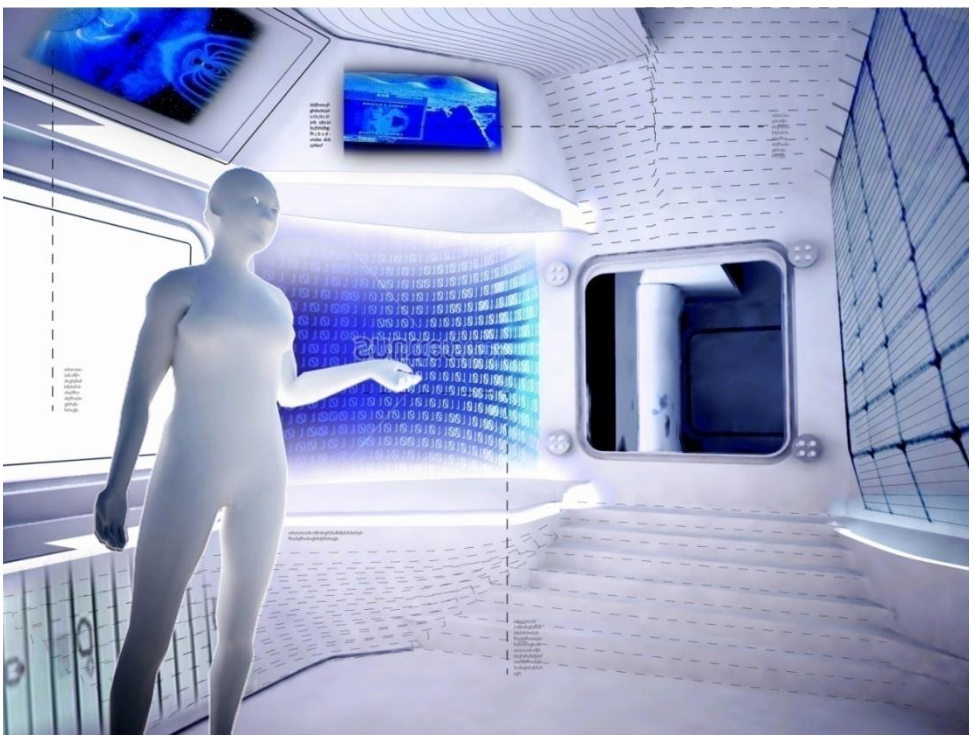


Figure 19d. *depicts the interior volume of the modular cell of the mobile habitat element.(credit B.Farahi)*

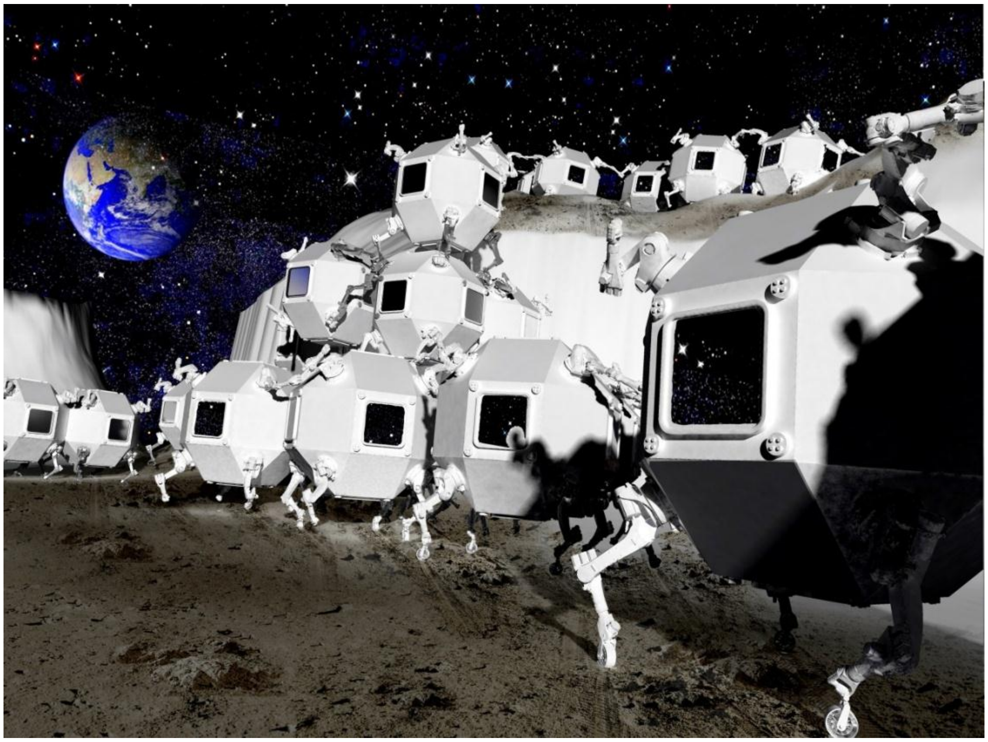


Figure 19e. *shows one potential configuration of cellular habitats that attempts to conserve energy by congregation and adhering to opportune natural terrain to combat the extremes of lunar environment.(credit B.Farahi)*

Figure 20. *The graduate Architecture Moon Studio team members at the final reviews attended by faculty, and external reviewers from NASA and industry.*

V. Conclusion

Contour Crafting technology and the co-robotic strategy offer new opportunities for lunar settlement infrastructure buildup and establishment.

By combining NASA assets now in development and testing phases at simulation sites like D-RATS, it may be possible, using innovative technologies and strategies like CC and co-robotics, to achieve building typologies and building construction efficiencies that were not possible before.

Conceptual designs developed within the schools of engineering and architecture at USC, employing unique interdisciplinary principles, depict a potential variety of infrastructure and allied elements that are possible using CC technology and co-robotics.

Architects are, by virtue of their education, traditionally strong in the conceptual, graphic and visualization aspects of product synthesis, while engineers are adept in programming techniques and analytical methods. “Architecting” is the term used in systems engineering to indicate the art and science of complex system synthesis[Rechtin, 1990].

More studies that employ the synergies inherent in combining the best practices of both the architectural and engineering professions are warranted. Both disciplines are needed to work in concert to expand the creative envelopes of design and fabrication, especially in pioneering new concepts in outer space exploration and development activity, with powerful, enhancing and even radical ramifications for design, building and physical infrastructure development technologies and strategies here on Earth.

Once developed and deployed on the lunar and Martian surfaces, the same technologies may be modified and adopted for use here on Earth. Advanced robotic technologies like Contour Crafting, when combined with new strategies like co-robotics and manufacturing automation, offer promise to radically change the way buildings are erected and serviced.[Khoshnevis etal., 2012]

The myth of robots displacing and eliminating humans from the labor force not withstanding, robotic building technologies like CC vastly improve the rate of buildup and efficiency of the construction industry, while removing humans from hazardous conditions on the building site and elevating them to a supervisory, maintenance and critical anomaly resolution roles. Such technologies hold promise for erecting structures quickly in remote areas, in disaster zones, both natural or manmade.[Gluck 2012]

Safety, rate of buildup and economics of construction are all impacted favorably by this synergetic approach to building that is fully scalable, ranging from erecting small projects like residences all the way to very large scale developments including factories and manufacturing complexes and even entire cities.

Acknowledgments

This work is the joint interdisciplinary effort of the faculty and students of the Schools of Engineering and Architecture at USC. The work was facilitated by the pioneering activities of Prof.Behrokh Khoshnevis, the inventor of the Contour Crafting technology in the Dept. of Industrial Systems Engineering, who was instrumental in finding support for activities that led to this report. Special thanks are due Dean Yannis Yortsos of the Viterbi School of Engineering and Dean Qingyun Ma of the School of Architecture who clearly saw the synergies residing in both schools and brought them together to make the Arch 605 Graduate Moon Studio happen, the products of which are displayed in this paper. Thanks are due the Architecture faculty, Profs. Anders Carlson and Neil Leach, who spent many hours figuring the pedagogy and schedules for the studio including inviting a series of topical experts to talk to the studio. We are grateful to the visiting lecturers from NASA and industry and academia, who spent time with our students as well. A special thanks to all the students who contributed effectively to the Moon Studio and were a pleasure to interact with during the Spring 2012 semester.

Dedication

This paper is dedicated to the all American hero and global icon Neil Armstrong(August 5, 1930 – August 25, 2012), who overrode the LEM computer and manually commanded the Apollo 11 lunar lander to a touchdown in the Sea of Tranquility on the lunar surface to safely land the first men on the Moon. Distinguished alumnus of USC and graduate of the department of Aerospace Engineering, Mr. Armstrong gave the commencement address to USC graduates in May of 2005.

“I hope you have become comfortable with the use of logic, without being deceived into concluding that logic will inevitably lead to the correct conclusion.”

–Neil Armstrong, May 13th, 2005 USC commencement address at the Alumni Memorial Park.

Neil Armstrong models in the Gemini G-2C training suit, laced boots and all, perhaps the finest aesthetic that heralded the arrival of American design and style at the dawn of the space age. Visuals like these(note lighting and background fade) evoked inspiration and awe in a new generation, ready to take on spaceflight in the early 1960s.

References

Aerospace Corporation,(2004) "Hubble Space Telescope Servicing Analyses of Alternatives, Final Delivery Executive Summary," August 3, 2004, Aerospace Corporation.

Arnold, J.R. (1979) Ice in the lunar polar regions. *J. Geophys. Res.*, **84**, 5659–5668.

Armstrong, N., (2005) Commencement Address to USC Graduates, May 13th, 2005

http://www.usc.edu/dept/pubrel/specialevents/commencement/documents/PastSpeeches-Armstrong.pdf

Augustine, N. (2009) Seeking a Human Spaceflight Program Worthy of a Great Nation: Review of Human Spaceflight Plans Committee Washington DC.

Bak, P. (1996). *How Nature Works: The Science of Self-Organized Criticality*. New York: Copernicus. ISBN 0-387-94791-4.

Ball, J.R. and Evans, C.H.Jr. (eds) (2001) *Safe Passage: Astronaut Care for Exploration Missions*, Committee on Creating a Vision for Space Medicine during Travel Beyond Earth Orbit, National Academy Press, Board on Health Sciences Policy, Institute of Medicine. Washington, DC.

Benaroya, H. and Bernold, L. (2008) Engineering of lunar bases. *ActaAstronautica*, **62**, 277–299.

Christensen etal., (2009) A Roadmap for US Robotics:From Internet to Robotics, Sponsored by CCC and CRA, Georgia Institute of Technology

Clarke, A.C. (1954) *The Exploration of the Moon* (ed. R.A.Smith), Harper & Brothers, New York.

Cohen, M. (2003) Mobile lunar and planetary bases. AIAA–2003-6280, AIAA Space 2003 Conference, Long Beach, CA, September 23–25, 2003, American Institute of Aeronautics and Astronautics.

Cohen, M. (2002) Selected precepts in lunar architecture. 34th COSPAR Scientific Assembly, The Second World Space Congress, held 10–19 October, 2002 in Houston, TX, USA.

Colaprete, A., Ennico, K., Wooden, D., Shirley, M., Heldman, J., Marshall, W., Sollitt, L., Asphaug, E., Korycansky, D., Schultz, P.,Hermalyn, B., Galal, K., Bart, G.D., Goldstein, O., Summy, O. and LCROSS Team. (2010) Water and more: An overview of LCROSS impact results. 41st Lunar and Planetary Science Conference, Lunar and Planetary Institute, Houston, March 2010.

Dillow, C.,(2012) I Am Warplane, Popular Science, August 13th, 2012.http://www.popsci.com/technology/article/2012-07/i-am-warplane?single-page-view=true

Duke, M.B. (ed.) (1998) Workshop on using *In Situ* Resources for Construction of Planetary Outposts LPI Technical Report Number98-01 LPI/TR–98-01.

Eastman, C, Teicholz, P., Sacks, R.,and Liston, K., (2008). *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers*, Wiley. ISBN 978-0-470-18528-5

Eckart, P. (1996) *Spaceflight Life Support and Biospherics*, Microcosm/Kluwer Publishers, Hawthorne, CA/Dordrecht, ISBN .

Eckart, P. (2006) *The Lunar Base Handbook: An Introduction to Lunar Base Design, Development, and Operations*, 2nd edn, McGraw-Hill, New York, p. 860.

Ehricke, K. (1984) Lunar industrialization and settlement – Birth of a polyglobal civilization, in *Lunar Bases and Space Activities of the 21st Century* (ed. W.W.Mendell), Lunar and Planetary Institute, Houston, Texas, pp. 827–855, ISBN .

Fong, T., IllahNourbakhsh, and Kerstin Dautenhahn(2002) A Survey of Socially Interactive Robots: Concepts, Design, and Applications, CMU-RI-TR-02-29, The Robotics Institute, Carnegie Mellon University, Pennsylvania 15213

Glaser, P. (1968) Power from the Sun: Its future. *Science*, **22**, 857–861.

Gluck, M.,(2102) Design for the Final Frontier, Architectural Record, McGraw Hill Construction, August 27, 2012, http://archrecord.construction.com/news/2012/08/120823-Design-for-the-Final-Frontier.asp

GM News (2010) "NASA and GM Create Cutting Edge Robotic Technology", NASA Hq. Feb04, 2010. http://www.nasa.gov/home/hqnews/2010/feb/HQ_10-035_R2.html

Heiken, G.H., Vaniman, D.T. and French, B.M. (eds) (1991) *Lunar Sourcebook: A User's Guide to the Moon*, Cambridge University Press, Cambridge.

Hodges, K.V., Schmitt, H.H., Fong, Terry(2010) A New Approach To Advanced Planetary Field Geology, Intelligent Robotics Group, NASA Ames Research Center, Moffett Field, CA2010 GSA Denver Annual Meeting (31 October –3 November 2010)Paper No. 19-2

Hopkins, J.and Pratt, W. (2011) Comparison of Deimos and Phobos as Destinations for Human Exploration, and Identification of Preferred Landing Sites, Lockheed Martin , AIAA Space 2011 Conference, September 27, 2011

H. Hua, J. Mrozinski, K. Shelton, A. Elfes, J. Smith, W. Lincoln, C.R. Weisbin, V. Adumitroaie,(2008) "Analyzing Lunar Mission Architectures Using An Activity Planner for Optimizing Lunar Surface Human-Robot Operations", Conference on System Engineering Research, Los Angeles, CA, April 4-5, 2008.

Huntoon, C.L., Antipov, V.V. and Grigoriev, A.I. (1996) Humans in spaceflight (Book 2), in *Space Biology and Medicine III* (edsA.E.Nicogossian and O.G.Gazenko), Joint US Russian Publication, Nauka Press, Moscow and Washington DC., pp. 539–45.

Khoshnevis, B.M., Bodiford, P., Burks, K.H., Ethridge, E., Tucker, D., Kim, W., Toutanji, H. and Fiske, M.R. (2005) Lunar contour crafting – A novel technique for ISRU based habitat development. AIAA Space 2005 University of Southern California Information Sciences Institute, Marina del Rey, CA, 90292.

Khoshnevis, B., Carlson A., Leach N., & Thangavelu, M.,(2012) Contour Crafting Simulation Plan For Lunar Settlement Infrastructure Build-Up, Earth and Space Conference: Engineering for Extreme Environments, April15-18, Pasadena, CA, American Society of Civil Engineers.

Lin, T.D, Tseng, L. and Choupp, S. (1982) Lunar concrete made with the dry-mix/steam-injection method. *J. Aerosp. Eng.*, American Society of Civil Engineers.

Lin, T.D., Love, D. and Stark H. (1987) Physical properties of concrete made with apollo 16 lunar soil sample.In Barbara Faughnan and Gregg Maryniak (PDF). Space Manufacturing 6: Proceedings of the Eighth Princeton/AIAA/SSI Conf., May 6–9, 1987. American Institute of Aeronautics and Astronautics, pp. 361–366.

W. Lincoln, C. R. Weisbin, A. Elfes, J. Smith, H. Hua, K. Shelton, J. Mrozinski, (2008)"Linking Technology Capability to Human-Robot Mission Productivity," AIAA Space 2008, San Diego, CA, September 9-11, 2008.

Logsdon, J. (1970) *The Decision to Go to the Moon: Project Apollo and the National Interest*, MIT Press, Cambridge.

Logsdon, J. (2008) *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program*, vol. **1–10**, National Aeronautics and Space Administration, Washington DC.

Mendell, Wendell W. (1985) *Lunar Bases and Space Activities of the 21st Century*, Lunar and Planetary Institute, Houston, Texas, ISBN .

Mendell, W.W. (1988) The Second Conference on Lunar Bases and Space Activities of the 21st Century Edited by W. W. Mendell. NASA Conf. Publication 3166, Volume 1 (Parts 1–4) & Volume 2 (Parts 5–8), 1992, 706.

NASA, 2004, "Hubble Space Telescope Robotic Servicing Mission Project," Hubble Space Telescope Review Team Report, July 26, NASA Independent Program Assessment Office, Washington, D.C.

National Research Council Space Studies Board, (2005)Assessment of Options for Extending the Life of the Hubble Space Telescope: Space Studies Board, Final Report, National Academy Press 2004

NASA (2007) The Global Exploration Strategy: The Framework for Coordination. Retrieved from

NASA:http://www.nasa.gov/pdf/178109main_ges_framework.pdf.

NASA JPL(2012) Mars Science Laboratory(MSL) Entry Descent and Landing(EDL),http://mars.jpl.nasa.gov/msl/

National Robotics Initiative(NRI)(2012) The realization of co-robots acting in direct support of individuals and groups, NSF11-553, http://www.nsf.gov/pubs/2011/nsf11553/nsf11553.htm

Ondler, M.(2010) Project M History and Driving Philosophy, NASA JSC

Rechtin, E. (1990) Systems Architecting: Creating & Building Complex Systems, 1st edn, Prentice-Hall, Englewood Cliffs, NJ (December 1, 1990) ISBN-13:978-0138803452.

Robinson, M.(2010) The Lunar Reconaissance Orbiter Camera(LROC) Science Operations Center, Arizona State University, http://www.lroc.asu.edu/

Robonaut 2 Fact Sheet NASA - http://www.nasa.gov/pdf/464887main_Robonaut2FactSheet.pdf

G. Rodriguez and C.R. Weisbin. "A New Method to Evaluate Human-Robot System Performance," Special Issue of Journal on Autonomous Robotics, Kluwer-Publishers, Vol. 14, pages 165-178, March 2003.

G. Rodriguez, C. Weisbin and R. Easter(2002)"A New Method for Human-Robot System Resiliency Evaluation," JPL Publication 02-26, November 2002.

Ruoff, C., "Overview of Space Robotics,"(1994) in *Teleoperation and Robotics in Space*,S. Skaar, C. Ruoff, Eds. AIAA press (1994)

Ruoff, C.,(1999) "Technologies for Mars Exploration and Sample Return," Paper AIAA 99-4447, *AIAA 1999 Space Technology Conference,* Albuquerque, NM (September 1999)

Sadler, P., Furfaro, R., Giacomelli G.A. and Patterson, R.L. (2009) Prototype BLSS lunar greenhouse.SAE International Paper No. 09ICES-0250. Proceedings ICES Conference, Savannah, GA.

Schmitt, Harrison H. (2006) *Return to the Moon: Exploration, Enterprise, and Energy in the Human Settlement of Space*, Praxis Publishing, Chichester, UK, p. 336.

Schreckenghost, D., Terrence Fong, Tod Milam., Human Supervision of Robotic Site Surveys, NASA Ames Research Center, Moffett Field, CA 94035

Schrunk, D., Sharpe, B., Cooper, B. and Thangavelu, M. (2007) *The Moon: Resources, Future Development, and Settlement*, 2nd edn, Springer-Praxis, New York, ISBN .

Simon H.A. (1962): The Architecture of Complexity, Proceedings of the American Philosophical Society 106, p. 467-482

Simon, T. and Sacksteder, K.(2007) In Situ Resource Utilization (ISRU)Development and Incorporation Plans, Technology Exchange Conference, Galveston

Skaar, S. and Ruoff, **C.,** Eds.(1994) *Teleoperation and Robotics in Space,* AIAA press (1994)

SSB-Space Studies Board,NRC (2005)Assessment of Options for Extending the Life of the Hubble Space Telescope: Space Studies Board, Final Report, National Academy Press 2004

Stephens, S.K., Willenberg ,H.J., Metrics for In-Space Telescope Assembly Techniques(2002), NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91009

Thangavelu, M. and Dorrington, G.E. (1988) MALEO: Modular assembly in low earth orbit; strategy for return to the moon. ST88 – 15 International Astronautical Federation Conference, Bangalore, India.

Thangavelu, M. (2000) Lunar Rock Structures, Return To The Moon II. Proceedings of the 2000 Lunar Development Conference, Las Vegas, NV. Edited published by the Space Studies Institute, NJ. ISBN 0-9701278-0-4, 106–08.

Thangavelu, M. (2008) Critical Strategies For Return To TheMoon: Altair dust mitigation and real time teleoperations concepts. Joint Annual Meeting of LEAG-ICEUM-SRR, # 4056, Cape Canaveral, FL, Oct 2008.

Thangavelu, M. and Mekonnen, E. (2009) Preliminary infrastructure development for Altair Sortie Operations. AIAA Space 2009 Conference, September 2009, Pasadena, CA.

Thangavelu, M. (1992) Logistics For The Nomad Explorer Assembly Assist Vehicle: An Architecture For Rapid Global Lunar Infrastructure Establishment. IAF92-0743, 43rd IAF and World Space Congress, Washington DC.

Thangavelu, M. *et al.* (2003) Elements of sustainable lunar base in the south polar region, International Lunar Conference, Hawaii,http://www.spaceagepub.com/pdfs/Khaled.pdf.

Thangavelu, M.,(2010) “Living on the Moon”, Encyclopedia of Astronautical Engineering, John Wiley & Sons.

Toups, L., Rojdev, K., Hong, T., Hafermalz, S., Hunkins, R. and Valle, G. (2009) Inflatable Habitat Health Monitoring: Implementation, Lessons Learned, and Application to Lunar or Martian Habitat Health Monitoring NASA Johnson Space Center, Houston, TX 77058 USA.

US Army (1959) Project Horizon, Vols. 1–lV.

C. R. Weisbin, J. Mrozinski, W. Lincoln, A. Elfes, K. Shelton, H. Hua, J. H. Smith, V. Adumitroaie, R. Silberg,(2010) "Lunar Architecture and Technology Analysis Driven by Lunar Science Scenarios," Systems Engineering Journal, Vol. 13, Number 3, 2010

C.R. Weisbin, A. Elfes, J.H. Smith, H. Hua, J. Mrozinski, K. Shelton, "Collaborative Human-Robot Science Exploration on the Lunar Surface,"(2007) The Workshop on Exploration: The Lunar Outpost and Beyond," Houston, Texas, October 1-5, 2007.

C. R. Weisbin, J. Mrozinski, H. Hua, K. Shelton, J.H. Smith, A. Elfes, W. Lincoln, V. Adumitroaie, R. Silberg,(2008) "Human-Robot Lunar Exploration: Pressurized vs. Unpressurized Rovers," Proceedings of the 19th International Conference on System Engineering, pages 8-12, University of Nevada, Las Vegas, NV, August 19-21, 2008.

C. R. Weisbin, J. Mrozinski, W. Lincoln, A. Elfes, K. Shelton, H. Hua, J. H. Smith, V. Adumitroaie, R. Silberg,(2010) "Lunar Architecture and Technology Analysis Driven by Lunar Science Scenarios," Systems Engineering Journal, Vol. 13, Number 3, 2010

C.R. Weisbin, A. Elfes, J.H. Smith, H. Hua, J. Mrozinski, K. Shelton, "Collaborative Human-Robot Science Exploration on the Lunar Surface,"(2007) The Workshop on Exploration: The Lunar Outpost and Beyond," Houston, Texas, October 1-5, 2007.

Wheeler, K. R., Martin R., Allan M.B., Willeke, T.,(2005) PREDICTIVE INTERFACES FOR LONG-DISTANCE TELE-OPERATIONS, Intelligent Systems Division, NASA Ames Research Center, MS 269-1, Moffett Field, CA, USA 94035, Proc. 'ISAIRAS 2005 Conference', Munich, Germany, 5-8 September 2005 (ESA SP-603), September 2005

The Whitehouse(2012) Report To The President On Capturing Domestic Competitive Advantage In Advanced Manufacturing, Executive Office of the President, President's Council of Advisors on Science and Technology, July 2012 http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_amp_steering_committee_report_final_july_17_2012.pdf

Whittaker, Red etal.,(2009), Configuring innovative regolith moving techniques for lunar outposts, US Chamber of Commerce Programmatic Workshop on NASA Lunar Surface Systems Concepts, Astrobotics Technology Inc.,

Zuber, M.,(2010) Lunar Orbiter Laser Altimeter-LOLA Data Archive, MIT, http://imbrium.mit.edu/

Afterword

With the exponentially marching advance of science and applied technology, every day, every moment, humanity becomes a more sensitive and refined species. We continue to become more situationally aware of, and sensitive to, the plight of fellow human beings around the world, aided by speed-of-light information technologies. Our species-links to the biosphere become more evident and clearer, allowing us to react in ways never before thought possible.

Space exploration is one specific and unique arena of human endeavor in which we see professional interdisciplinary convergence. Immersed in such a dynamic information rich environment, imaginative and creative projects like lunar and Mars exploration and settlement are helping us become even more aware and sensitive to the universe around us, making us an even more refined species. And that is good.

Architects and engineers, are in a unique position, as the professionals endowed with the tools and knowledge that allow us to create and service the physical infrastructure continuum of modern civilization. In concert, we must use our sensibilities to project Vision, deeply rooted in our history, to create the living and working environment of tomorrow, and space exploration and development is a promising avenue to exercise their combined synergetic skills.