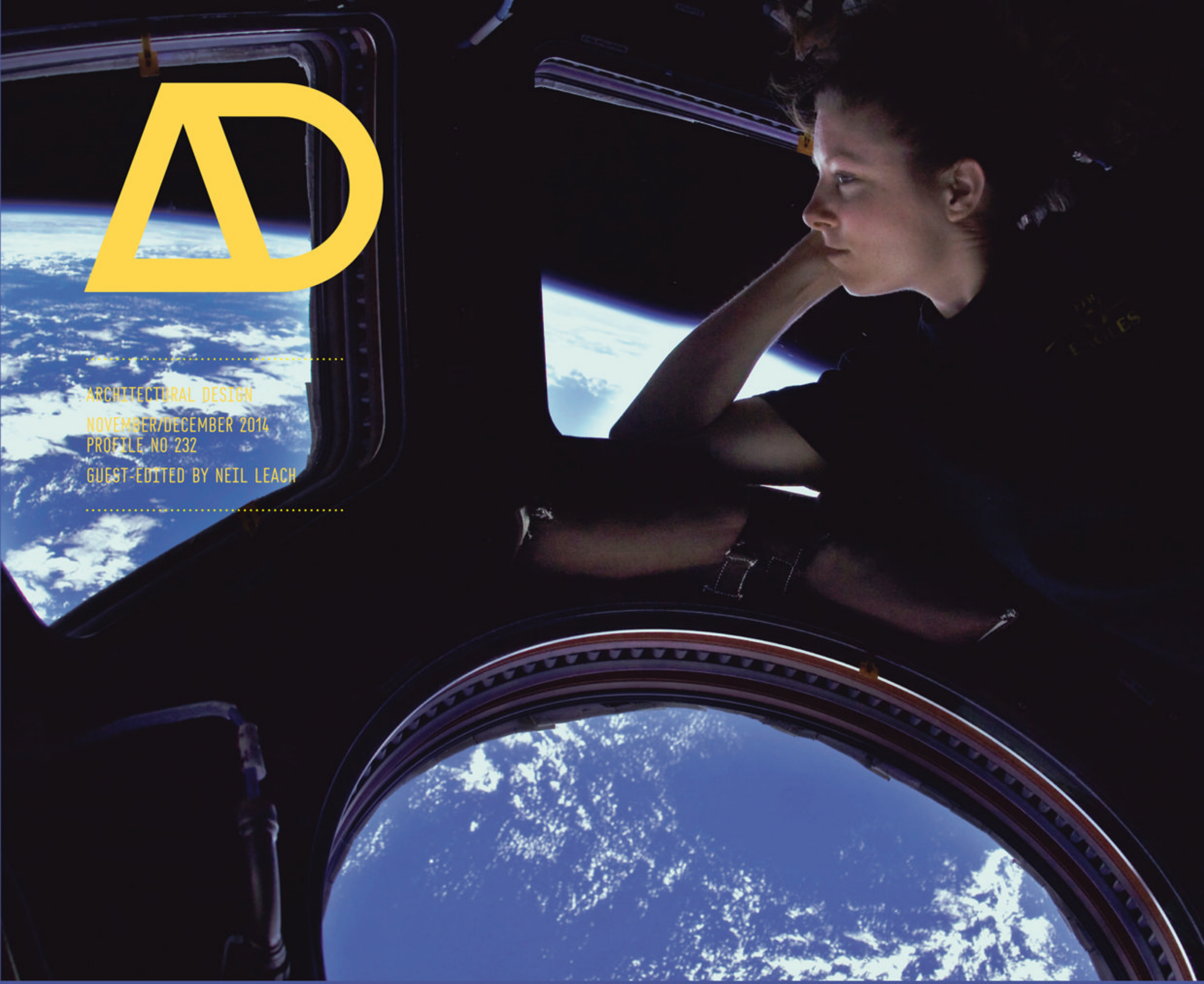

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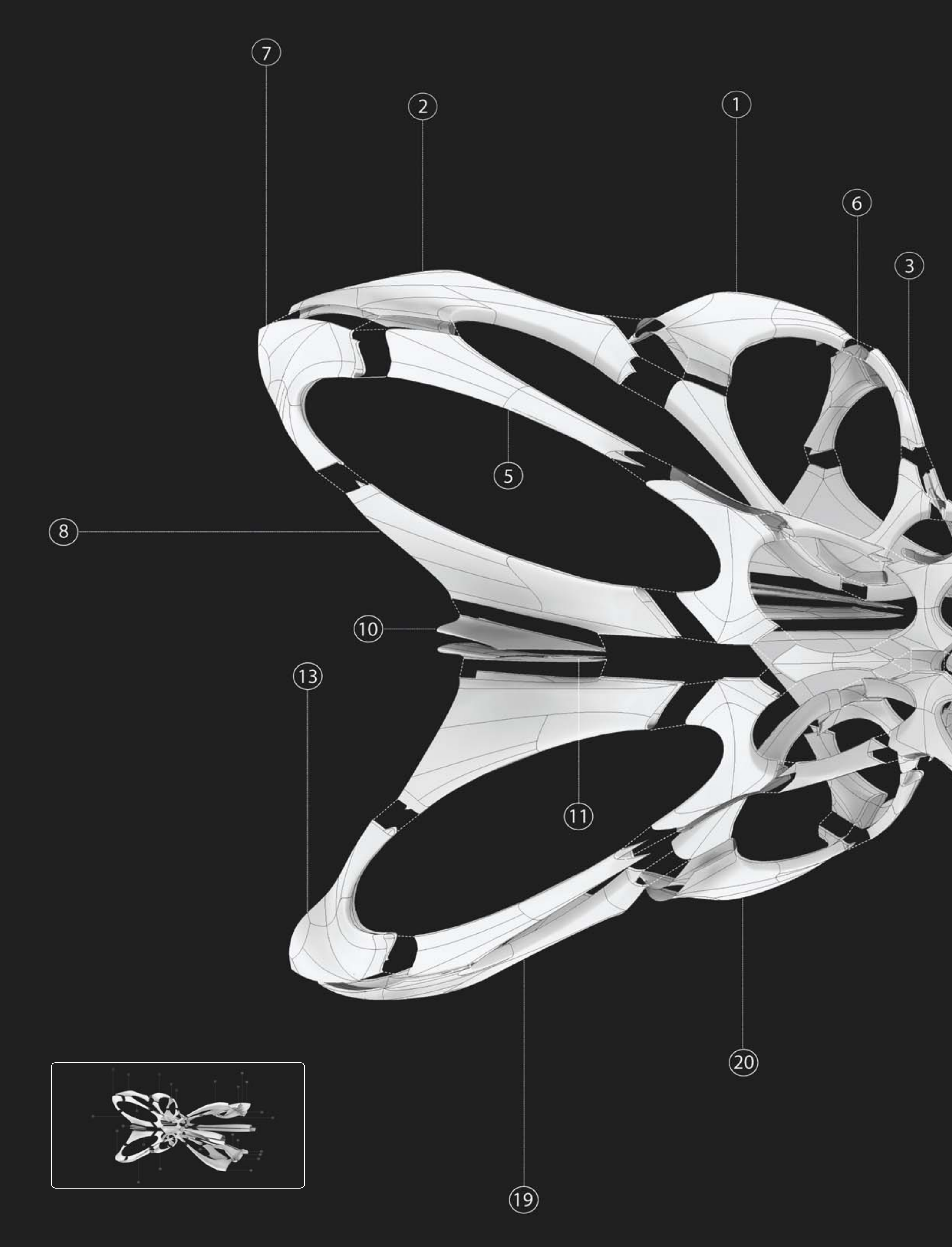
SPACE ARCHITECTURE

THE NEW FRONTIER FOR DESIGN RESEARCH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SPACE ARCHITECTURE: THE NEW FRONTIER FOR DESIGN RESEARCH

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The future of the past is in the future
The future of the present is in the past
The future of the future is in the present
— John McHale, 1965, in AD 2000+, February 1967, p 64

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Inside front cover: Julia Koerner, Space Collective (detail), (tutors: Greg Lynn and Brennan Buck), MArch, University of Applied Arts, Vienna, 2007. © Julia Koerner

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EDITORIAL

Helen Castle

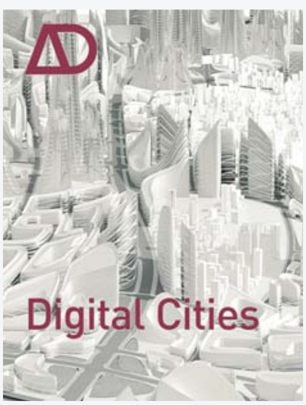
Space represents a unique chance to look up and beyond ourselves. It is an opportunity that has not been missed by AD over the years – forever casting its eye on the horizon for what might be happening next culturally, socially and technologically. *Space Architecture* is the third issue of AD on the subject. The first, seminal issue *2000+* was published in February 1967 under the editorship of Monica Pidgeon and Robin Middleton (technical editor). The material was compiled and much of it written by scholar–artist and Father of Pop Art John McHale, who was then Executive Director and Research Associate of the World Resources Inventory at Southern Illinois University. With its red, eye-catching cover depicting the head of an astronaut, it captured the zeitgeist with two articles by Buckminster Fuller, its late-1960s enthusiasm for technological hardware and everything space related. It also anticipated the lunar landings by two years. Pasted together from a whole range of astronautical engineering sources, it fully established AD's and its readerships' penchant for the nerdily technical. The second issue, guest-edited by Rachel Armstrong in April 2000, conspired to reinvigorate the enthusiasm of the design community in the astronautical and bring their attention to the new possibilities introduced by space tourism. Like the first issue, it also foreshadowed events by coming out a year before the first space tourist Dennis Tito blasted into space on the 28 April 2001.

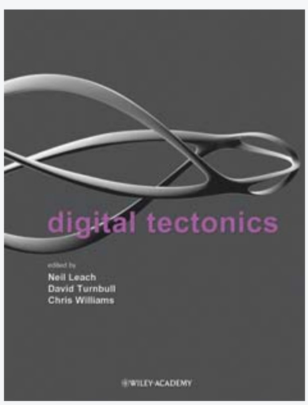
This third issue of AD on Space brings with it an entirely different emphasis on design research. It is guest-edited by Neil Leach, who has a distinguished career as an architectural educator and author, but is also a NASA Innovative Advanced Concepts Fellow working at the University of Southern California (USC) on a research project to develop a robotic fabrication technology to print structures on the Moon and Mars (see '3-D Printing in Space' on pp 108 –13 of this issue). Leach demonstrates how Space provides not only a test bed for new technologies, such as robotics, that are set to become game-changing for terrestrial architecture, but also provides a catalyst for pushing the boundaries in terms of ideas, imagination and lifestyles: whether it prompts inventive speculative design from the likes of Greg Lynn (pp 82–7) or seeks us to explore the climatic and practical challenges that might be thrown up by the human colonisation of the Moon or Mars. Moreover, for architects, designing for Space is now becoming less a matter of speculation and more one of live projects. This is epitomised by the engagement of a premier international firm like Foster + Partners on the design of Spaceport America in New Mexico and the firm's further participation in space research as a key collaborator in the European Space Agency (ESA) consortium that is investigating the potential of 3D printing on the Moon.

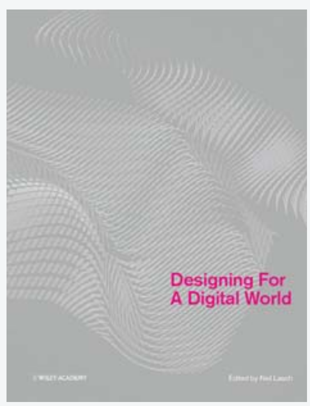
There is a neat circularity to this volume, as Rachel Armstrong provides the Counterpoint to this issue. With characteristic tenacity, she challenges readers to explore a wider notion of how planets might be developed as biological ecologies for habitation rather than as discrete territories for exploitation. AD

left: AD *2000+*, February 1967.

right: Rachel Armstrong, AD *Space Architecture*, April 2000.







Neil Leach, *AD Digital Cities*, 2009
This issue of AD looks at the impact of computation not only on the design of cities, but also on techniques of analysing and understanding them.

Neil Leach, David Turnbull and Chris Williams, *Digital Tectonics*, 2004
The book addresses the use of computation in designing structures and structural systems in architecture. In so doing it outlines both a structural turn in architecture, as structural efficiency becomes an increasingly important factor in design, and the impact of computation on structural design.

Neil Leach, *Designing for a Digital World*, 2002
This volume brings together some of the leading architects, philosophers and cultural theorists from across the globe to look at the impact of digital technologies on the world of design.

Neil Leach, Kristina Shea, Spela Videcnik and Jeroen van Mechelen, eifFORM installation, Academie van Bouwkunst, Amsterdam, 2003
Constructed in the Academie's courtyard, the design of this installation was generated using eifFORM, a software program that produces structurally efficient forms in a stochastic non-monotonic method, using simulated annealing.

ABOUT THE GUEST-EDITOR
NEIL LEACH

Neil Leach is an architect and theorist. He is currently Professor of Digital Design at the European Graduate School, Visiting Professor at Harvard Graduate School of Design (GSD) and Tongji University, and Adjunct Professor at the University of Southern California (USC), Los Angeles. He is also a NASA Innovative Advanced Concepts Fellow, working in collaboration with colleagues from USC on a research project to develop a robotic fabrication technology to print structures on the Moon and Mars. The project stems from deeper research into computational design and robotic fabrication technologies, especially Contour Crafting, a technology for layered concrete construction invented by Behrokh Khoshnevis, with whom he has collaborated for several years.

His research work on computational design and robotic fabrication technologies has taken the form of a series of publications, exhibitions and conferences. His publications in this field include: *Designing for a Digital World* (Wiley, 2002); *Digital Tectonics* (Wiley, 2004); *Emerging Talents, Emerging Technologies* (China Architecture and Building Press (CABP), 2006); *(Im)material Processes: New Digital Techniques for Architecture* (CABP, 2008); *AD Digital Cities* (Wiley, 2009); *Machinic Processes* (CABP, 2010); *Fabricating the Future* (Tongji University Press, 2012); *Scripting the Future* (Tongji University Press, 2012); *Digital Workshop China* (Tongji University Press, 2013); *Design Intelligence: Advanced Computational Research* (CABP, 2013); and *Swarm Intelligence: Architectures of Multi-Agent Systems* (Tongji University Press, 2014). He has also curated a series of exhibitions and associated conferences in this field including: 'Fast Forward>>' (Architecture Biennial Beijing (ABB), 2004); 'Emerging Talents, Emerging Technologies' (ABB, 2006); '(Im)material Processes: New Digital Techniques for Architecture' (ABB, 2008); 'Machinic Processes' (ABB, 2010); 'Swarm Intelligence: Architectures of Multi-Agent Systems' (Shanghai, 2010); 'DigitalFUTURE' (Shanghai, 2011); 'Interactive Shanghai' (Shanghai, 2013); and 'Design Intelligence: Advanced Computational Research' (Beijing, 2013).

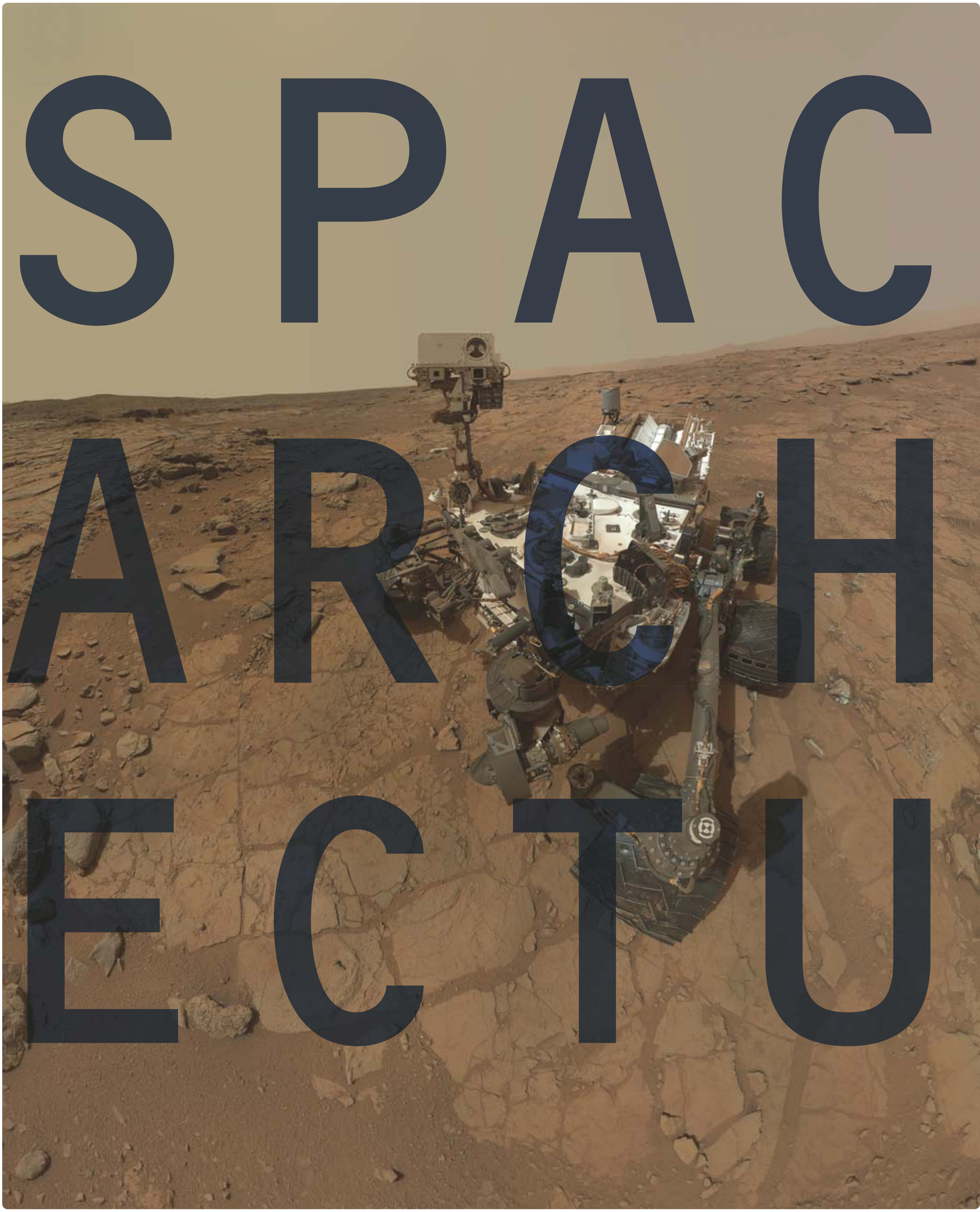
His other field of research is the intersection between architectural theory and critical theory/philosophy. His publications in this field include: *Rethinking Architecture: A Reader in Cultural Theory* (Routledge, 1997); *The Anaesthetics of Architecture* (MIT Press, 1999); *Millennium Culture* (Ellipsis, 1999); *Architecture and Revolution: Contemporary Perspectives on Central and Eastern Europe* (Routledge, 1999); *The Hieroglyphics of Space: Reading and Experiencing the Modern Metropolis* (Routledge, 2002); *Forget Heidegger* (Paideia, 2006); *Camouflage* (MIT Press, 2006); and *The Politics of Space* (Routledge, forthcoming).

He holds an MA and Diploma of Architecture from the University of Cambridge, and a PhD degree from the University of Nottingham, and is a registered architect in the UK. AD

INTRODUCTION

Neil Leach

Curiosity rover self-portrait, Mars, 3 February 2013
The self-portrait was taken on a patch of flat outcrop called John Klein, where the NASA rover was due to perform rock-drilling activities. The image is actually composed of dozens of exposures stitched together.



Space Shuttle Atlantis seen from the Mir space station, 29 June 1995
Fish-eye view of the Atlantis as seen from the Russian Mir space station during the STS-71 mission.

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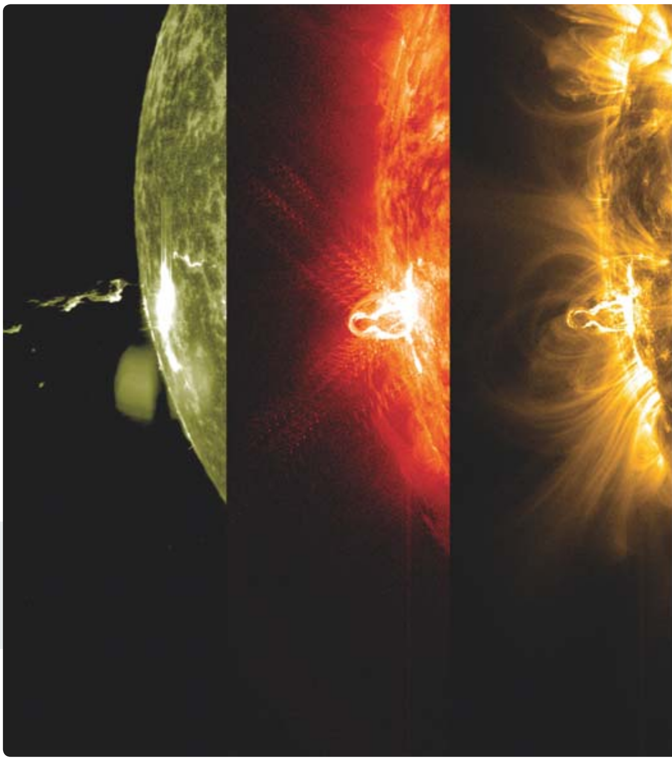
THE NEW FRONTIER FOR DESIGN RESEARCH

Architecture in Space is entering a new era. It is over 40 years now since the late Neil Armstrong became the first human being to set foot on the Moon. For many people space exploration has not advanced much since that historic moment, but in reality there have been numerous developments. Space exploration has taken on a collaborative international dimension through the International Space Station (launched in 1998) and other ventures. Likewise, the practice of one-off flights has given way to the introduction of reusable hardware such as NASA's Space Shuttle (operational 1981–2011). More recently, in 2011 the US sent the Curiosity rover, its most sophisticated robotic vehicle, to investigate the climate and geology of Mars. And other countries have joined the space industry, with China sending its first astronaut, Yang Liwei, into Space in 2003 and then landing its own lunar rover, Yutu (or Jade Rabbit), on the Moon in December 2013. Significant research has also been undertaken into harnessing energy from Space, and the space tourism industry is gearing itself up to send the first space tourists into low earth orbit.

Over the last decade there has been a fundamental shift in the space industry from short-term pioneering expeditions to long-term planning for colonisation and new ventures such as space tourism. Architects are now involved in designing the interiors of long-term habitable structures in Space, such as the International Space Station, researching advanced robotic fabrication technologies for building structures on the Moon and Mars, envisioning new 'space yachts' for the super-rich, and building new facilities such as the Virgin Galactic Spaceport America in New Mexico designed by Foster + Partners (2011). Meanwhile, the mystique of Space remains as alluring as ever, with architects including Greg Lynn (see his article on pp 82–8 of this issue) involved in design fictions set in Space, and educators such as Michael Fox of the California Polytechnic State University (Cal Poly – see pp 100–101), Larry Bell of the Sasakawa International Center for Space Architecture (SICSA) at the University of Houston (pp 118–21) and Lynn running design studios drawing upon ever more inventive computational design techniques.

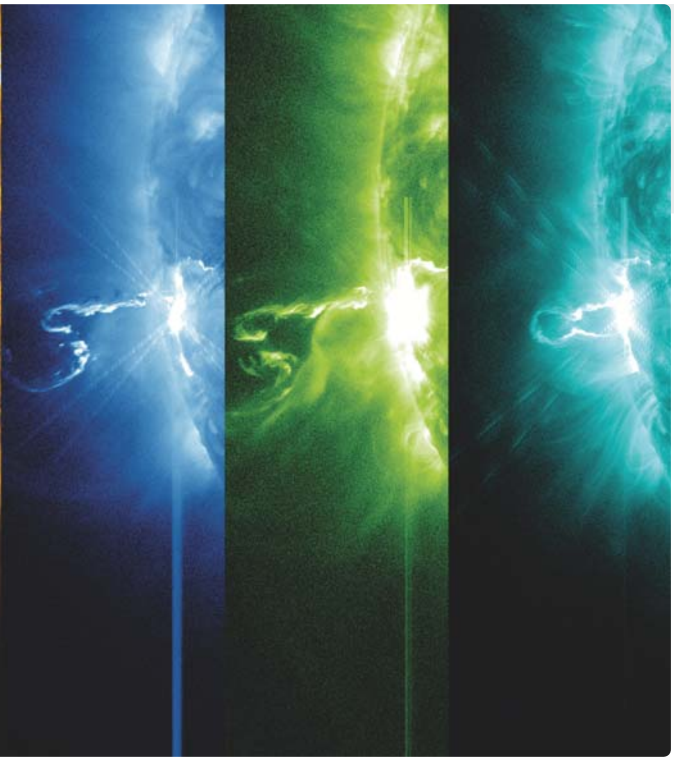
OVER THE LAST DECADE THERE HAS BEEN A FUNDAMENTAL SHIFT IN THE SPACE INDUSTRY FROM SHORT-TERM PIONEERING EXPEDITIONS TO LONG-TERM PLANNING



This issue of AD features the most significant of projects currently underway and highlights key areas of research in Space, such as energy, materials, manufacture and robotics. It also looks at how this research might be realised in outer space and the potential for applying it to conventional architectural design and construction. It is structured along the lines of the four key domains of Space Architecture: space colonisation, habitable artificial satellites, space tourism and terrestrial space-related industries.

Space Settlement

Space settlement remains one of the most contested topics. Should humankind continue to explore the potential of sending a handful of human beings to planets such as Mars and other celestial bodies, or should the emphasis be placed instead on relatively large-scale settlement programmes on the Moon? Contributors to this volume remain divided. Space architect Madhu Thangavelu (pp 20–29) favours the potential settlement of the Moon, as does fellow space architect Brent Sherwood (pp 16–19), who sets out the various future options in terms of space developments. Designer Andreas Vogler's MoonCapital proposal (pp 30–35) offers an architectural vision of such a project. Meanwhile, former astronaut and the second man to set foot on the Moon, Buzz Aldrin (pp 40–45), argues that the next important milestone is surely to send a human being to Mars, despite the unlikelihood of being able to bring that person back. Aerospace engineer and author Robert Zubrin (pp 46–53), himself a long-time passionate advocate of missions to Mars, agrees with Aldrin that we should be investing our energies in settling Mars, although his vision is slightly different.



NASA Solar Dynamics Observatory, Solar flares, 24 February 2014
The harvesting of solar energy remains a further potential opportunity in Space. These images show the first moments of an X-class flare in different wavelengths of light.

Space architects have also been involved in researching other concerns related to space settlement, exploring ways of constructing habitats and other infrastructural facilities on the Moon and Mars, which has developed considerably in the past few years, and devising novel rovers for traversing their surfaces, such as the ATHLETE moon rover developed by A Scott Howe (see pp 36–9). For example, a series of consortia are now exploring the potential of robotic fabrication technologies for printing structures on the Moon and Mars that echo the growing interest in 3D printing in general. These technologies can also be deployed in habitable artificial satellites for printing replacement parts and even for printing food. My own article on pp 108–11 of this issue offers an overview of developments in 3D printing in Space.

Habitable Artificial Satellites

In terms of habitable artificial satellites, despite the many speculative ideas promoted by a variety of designers, the International Space Station (or 'Alpha', as it is known in the space industry) remains the only actual human habitat that has been deployed in Space to date. In her article (co-authored with Rod Jones), Constance Adams, who was involved in the design and fabrication of Alpha, recounts the process (see pp 70–77).

While research has been conducted into other possible space habitats – some of which are featured in this issue – the experience of astronauts actually inhabiting the International Space Station has itself generated a valuable new field of research into the physiological and psychological problems of keeping human beings in Space for extended periods. What has become clear is that human beings face considerable obstacles if they are to survive in Space, given the recurrent problems of radiation, weightlessness and diet. In his article on pp 90–95, Ondřej Doule (chair of the Space Architecture Technical Committee at the American Institute of Aeronautics and Astronautics (AIAA)), considers the issue of gravity, which he considers to be the fundamental challenge in space exploration, not only in terms of the problems of weightlessness in space habitats such as Alpha, but also in launching rockets in the first place. Likewise, space architect Sandra Häuplik-Meusburger (pp 114–17) looks at the potential of different greenhouse systems in Space in which to not only grow vegetables, but also to provide some visual relief to the monotony of life on board. Equally, space architect Marc M Cohen (pp 78–81) describes his vision of a Water Wall whereby waste fluids are redeployed as a radiation shield for spacecraft.

NASA Mars Reconnaissance Orbiter, Proctor Crater, Mars, 9 February 2009
Photo taken by the orbiter's High Resolution Imaging Science Experiment (HiRISE) camera showing one of the many dunes composed of fine sand.

SpaceX Dragon capsule grappled by the International Space Station's Canadarm2 Mobile Servicing System (MSS), 20 April 2014
Private enterprise has emerged as one of the most important drivers within the space industry, with companies such as SpaceX playing an increasingly prominent role. Here, a SpaceX Dragon craft is grappled by Canadarm2 as it delivers supplies.

NOT ONLY DO CERTAIN TECHNOLOGIES USED ON EARTH OWE THEIR ORIGINS TO DEVELOPMENTS IN THE SPACE INDUSTRY, BUT ALSO THE WHOLE OF THE SPACE INDUSTRY IS ULTIMATELY CONDITIONED BY TERRESTRIAL CONCERNS.

Michael Maltzan Architecture, New building for NASA's Jet Propulsion Laboratory (JPL), Pasadena, California, 2010
In this proposal for the new JPL building, the upper courtyard, with its reflecting fenestration, gives the impression of endless space.

Cosmonaut Sergey Ryazanskiy conducts a spacewalk outside the International Space Station, 9 November 2013
The Russian cosmonaut shown during a session of extra-vehicular activity (EVA).

Another great challenge facing the space industry is that of funding. At one stage, especially around 1964–6 when the Apollo programme was in full swing, the US space industry was the best resourced in the world. However, recent cutbacks and hiatuses in developing a viable replacement for the now retired Space Shuttle have led to the seemingly absurd situation where US astronauts are forced to hitch a lift with Russian rockets in order to reach the International Space Station. In his article, space architect Larry Bell (pp 118–21) laments the situation, and contrasts the heavy investment on the part of the Chinese space industry to the relative stagnation in the US.

Space Tourism

If, however, there is one area that has developed more rapidly than others it has been the private space industry. Not only have we witnessed the meteoric rise of private companies such as Space Exploration Technologies Corporation (SpaceX) in designing, manufacturing and launching advanced rockets and spacecraft to resupply Alpha, the emergence of space tourism as a viable commercial venture has also changed the game. In his article on pp 64–9, Ondřej Doule charts the emergence of this new industry that seems to hold so much promise for the future.

Terrestrial Space-Related Industries

Another aspect of the space industry is, of course, the design and construction of space industry buildings on Earth. This issue of AD features two recent terrestrial buildings.

JUST AS SCIENCE FICTION OFTEN INFORMS DEVELOPMENTS IN SCIENCE ITSELF, SO THE REALM OF 'DESIGN FICTIONS' CAN ALSO INFORM DESIGN.

Crew members in the Japanese Experiment Module (JEM), International Space Station, 8 November 2013
Nine crew members gather for a group portrait in the JEM, known as the Kibo laboratory. Russian cosmonauts are joined by astronauts from NASA, the European Space Agency (ESA) and Japan Aerospace Exploration Agency (JAXA).

Spaceport America (pp 56–9) , designed by Foster + Partners and constructed in the desert of New Mexico, services the Virgin Galactic space tourism initiative, and is the first of a series of such spaceports that will soon be offering paying tourists the opportunity of going into low earth orbit. And the Cultural Centre of European Space Technologies (KSEVT) (pp 60–63) was designed by a consortium of Slovenian architects, and constructed in the Slovenian town of Vitanje. Other notable projects include the – albeit unbuilt – design of Michael Maltzan Architecture for a new building for the Jet Propulsion Laboratory (JPL) in Pasadena, California.

Indeed the whole relationship between Earth and the space industries is an interesting and complex one. In my article on pp 54–63, I offer an overview of this connection. Not only do certain technologies used on Earth owe their origins to developments in the space industry (and here one can also imagine the potential of 3D printing techniques designed for the Moon being used for arid places on Earth, such as the desert), but also the whole of the space industry is ultimately conditioned by terrestrial concerns. Space, as such, becomes a mirror that reflects human concerns on Earth, and it is important not to overlook the significance of terrestrial ambitions in determining the course of the space industry.

Space Fantasies

Finally, no overview of developments in any field is complete without a degree of fantasy. Just as science fiction often informs developments in science itself, so the realm of 'design fictions' can also inform design. Included in this issue are the speculative projects of Greg Lynn (pp 82–9), completed in association with Alex McDowell, a designer for the Hollywood movie industry, and Peter Frankfurt, founding partner of the Imaginary Forces design agency. Equally, a number of space fantasies are included among the student projects featured on pp 96–107, which range in outlook from purely speculative design fictions to relatively serious attempts to operate realistically within the testing constraints of Space Architecture.

Put together, what we have is a snapshot of the latest developments in Space Architecture. What becomes clear is that there have been considerable activities going on in recent years that demonstrate that the space industry is alive and well. But they also reveal the versatility of the architectural imagination. No longer constrained by the limitations of terrestrial architecture, space architects are now exercising their imagination within the space industry, designing not only habitats for Space, but also working on other aspects of habitation – methods of building structures and ways of inhabiting them afterwards.

Rumours of the death of the space industry are greatly exaggerated. AD

Brent Sherwood

International Space Station, view of the Kamchatka Peninsula from the Russian segment, 2012
The view from 240 kilometres (150 miles) above Earth changes constantly; weather, sea state, time of day, seasons, and natural and man-made events paint stunning scenes that pass from view in just minutes.

WHAT NEXT FOR HUMAN SPACE FLIGHT?

Space travel is undergoing a significant period of transformation. While exploration in the last six decades has been driven by government-funded exploration by the major powers, the possibilities are now opening up for a Space Architecture that diversifies and caters for leisure, large-scale industrialisation and permanent settlement. Experienced space architect **Brent Sherwood** brings into focus four potential futures for human space flight – experiencing, exploring, exploiting and settling.

Fifty thousand generations ago, Homo sapiens appeared. In just the last 1 per cent of our time on Earth, we began making architecture to tame harsh environments and express physical, psychological, sociological and aspirational needs. Now, in just the final hundredth of 1 per cent of our time, we have started pressing into places utterly alien to our origins and our being: the Arctic, air, undersea and Space.[1]

Off-earth, we find a combination of conditions unlike any encountered before by living things: absence of weight; unfiltered, unending sunlight; cold so deep it liquefies air; lethal radiation streaming from solar storms and dying stars; distances too vast for direct conversation; and alien landscapes stranger than we might dare imagine. But great promise nonetheless lures us to explore and conquer Space: adventure and technical challenge, new sensations and vistas, a humbling perspective of ourselves, and inexhaustible energy and material resources.

So far, fewer than a thousand people have flown in Space. Despite our hard-won experience, we know nothing at all about Space Architecture for leisure, large-scale industrialisation or permanent settlement. But depending on the future we design, by the end of this century we could know most of these fundamentals – we live in a pivotal time. Private investment and profit making in space flight are just beginning; government space flight programmes – the National Aeronautics and Space Administration (NASA) in the US, the European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), Russian Federal Space Agency (RSA), China National Space Administration (CNSA) and the Indian Space Research Organisation (ISRO) – will continue to set the table for many decades because space technologies are so complex.

Four futures for human space flight – experiencing, exploring, exploiting or settling[2] – are possible, and eventually all are likely, yet we cannot afford them all at once. The technology choices we are making today are already determining which future our children will see in the 2050s.

Experiencing Space

Two-week vacations in low earth orbit could be routine by mid-century. Like cruise ships, orbital resort hotels would course silently over the planet once every 90 minutes, through 18 sunrises and sunsets each day. Imagine the amenities: weightless staterooms with awesome views; gourmet meals of locally grown and globally imported food; zero-gravity swimming pools, discotheques, sports and performing arts; guided telescope tours of Earth; and space-walking excursions into the vacuum.

Leisure travel in earth orbit is a marketable experience: the ride of your life (10 minutes up and 45 down); the incomparable sensations of sustained weightlessness; and the solar system's most poignant, beautiful, ever-changing view out the window. Demonstrated flight safety can unleash the market, as happened for air travel. While today neither sufficient safety nor compelling destinations exist, both are achievable.

On its own, the commercial orbital leisure travel market will grow very slowly, catering to the hyper-rich and interrupted by the kind of spectacular accidents that teach aerospace lessons. The flight rate and research required to approach airline-like safety are beyond the means of today's commercial space flight entrepreneurs, all of whose plans and machines use technology originally developed by NASA. And today's space 'destination systems' also depend on government technologies.

But if government agencies were to commit to a vision of hundreds of thousands of ordinary people flying in earth orbit every year, progress would be much faster.[3] We could have safe spaceliners ferrying dozens of passengers on each flight. We could have technologies for resort destinations: large pressure vessels built in Space; big windows; weightless 'kitchen science'; leisure architecture; space surgery; rotating artificial gravity. No government is developing any of this today; and until someone does, this rich future will remain far off.

NASA's predecessor, the National Advisory Council for Aeronautics (NACA), developed the airfoil and engine technologies inside every modern commercial and military jet. As a result, air travel enables the way we live today. NASA and its partners could do it again, jumpstarting whole new industries like one-hour travel between London and Tokyo, and orbital resorts. Experiencing Space could be central to tomorrow's society.

Exploring Space

By mid-century, a small team of intrepid humans could stand on Mars. Despite an unbreathable atmosphere almost 200 times thinner than Earth's, Mars is nonetheless the least inhospitable planet within our reach. It has polar caps and night frost, wind-driven weather, and Grand Canyon-like landscapes. Its magnetic field died billions of years ago, exposing its atmosphere to stripping by the solar wind, and sending it into a permanent, desiccated deep freeze. But liquid water once hosted clement conditions; did life ever occur there?

Today we use robots for the primary exploration of remote places in Space. NASA human space flight became linked to exploration in 1961, when President Kennedy selected the 'Moonshot' from among a menu of barely feasible options as a highly visible, peaceful project to demonstrate US technological superiority over the Soviet Union. Although exploring planets with people was not actually the core purpose of the Apollo missions (1967–72), it has since been adopted as a raison d'être by space agencies around the world.[3]

Technical challenges limit human exploration to the Moon, near-earth asteroids, the moons of Mars, and Mars itself. About 90 times further than the Moon (as measured in travel days), Mars is the prize. Described as the 'ultimate destination', it is the most distant surface we could reach by mid-century.

The necessary investments are daunting: advanced in-space propulsion; very large space vehicles that decelerate to a soft landing within seconds;[4] nuclear power; extraction of propellant from the tenuous Mars atmosphere; machinery and medical means to survive three years away from Earth; isolation of human biology from the Mars environment; and many others. Most would yield spin-off benefits unforeseeable today. And at the project's culmination, humankind would be awed by live video of the 'first Martians'. As long as memories of Apollo guide our choices, exploring Space will be the vision.

Curiosity rover, view of Glenelg, Gale Crater, Mars, 2013
top: With seasons, weather, frost, complex geological history and even the possibility that life once arose there, Mars presents humanity with an eerily familiar landscape to explore and tame.

International Space Station, view of the Nile Delta at night from the Russian segment, 2012
above: Flying over most of Earth's population centres and seeing 18 sunrises and sunsets each day highlights the inherently international nature of experiencing Space.

Exploiting Space

Imagine a world where electricity comes from the sky, rather than from burning fossil fuels; a world where precious metals, mined on the Moon and harvested from captured asteroids, are imported from Space in vast quantities. Space is almost inconceivably empty. But paradoxically it holds resources useful for a human future without limit. Today we use earth orbit for observation, telecommunications and astronomy. By mid-century, Space could also provide both energy and materials for the Earth at industrial scale.

The material resources of Space are diverse. The Moon has concentrations of 'rare earth elements' essential for high-tech products ranging from smartphone screens to the magnets in wind-turbine generators. It also contains recoverable amounts of a rare helium isotope that could fuel fusion power reactors, if they became feasible. A small fraction of asteroids are almost solid metal: iron and nickel laced with platinum-group metals vital for electronics and chemical manufacturing. Nudging the orbits of just a few of the tens of thousands of near-earth asteroids could bring such resources close enough to harvest, forever changing industrial economics. Industrial-scale operations would require investments – high-power space systems, electric propulsion, autonomous extraction and processing technologies – beyond the means of today's space entrepreneurs, but suitable for government development.

The most startling space resource weighs nothing at all. In Space, sunlight is about 40 per cent stronger than on Earth, and the Sun never sets. The fundamental technologies to convert sunlight into electricity, and then into microwaves for transmission to Earth, collect it with dipole antenna arrays over farmland and convert the power back into electricity for the grid are all well understood. The geosynchronous orbit, already industrialised for telecommunications and remote sensing, could be developed further into an inexhaustible source of clean electrical power, for export anywhere around the globe independent of night, weather or local conditions, and without blighting the landscape or damaging wildlife or the environment.[5]

Only a vast enterprise could supply a significant fraction of Earth's energy appetite: public-private partnerships, supplied by a steady stream of heavy cargo launches, fleets of robot workers and onsite crews, constructing and operating platforms in Space totalling as much area as the US National Highway System.[6] All this could be done if one or more spacefaring governments chose to lead the way towards a non-disruptive transition to a sustainable, post-petroleum world. Of the spacefaring nations, Japan is most interested in this vision, but no government has committed to it.

Energy-rich space operations could quickly open up other ways of exploiting Space: materials, tourism and other industries not yet conceived. Choosing this path, ironically so close to home, would focus space flight directly on one of the core geopolitical challenges of our century.

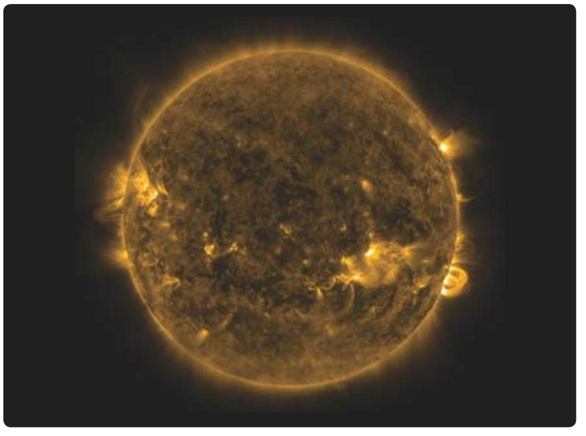
Settling Space

Imagine living in Space, raising your family in a strange, faraway place with unique challenges, experiences and joys, in a human community committed to taming a hostile frontier.

Eventually humankind will settle Space. Expansionary and adaptable, Homo sapiens has built to suit everywhere on Earth. Given territories to explore, resources to exploit and experiences to sell, humans will settle down and set up shop.

Settlement would bring space flight and architecture fully together. Beyond laboratories for researchers, dormitories for workers, spaceliners and cargo ships for tourists, settlers would need all the big and little items that make up self-sustaining human communities. They would generate power, find and extract raw materials, grow food, fabricate and recycle building materials and commodity goods, import and export specialised products, raise families, create governments, establish cultures and leave legacies – all off-earth, in circumstances without precedent. Learning to 'live off the land' in Space would teach us countless lessons, methods and technologies useful back on Earth, where we already see the human imprint looming larger with each passing decade.

Despite fantasies of Martian cities, the enormous cost of space transportation strongly favours settling the Moon first: just three days away, rich in raw materials for rocket propellant and construction, with low but useful gravity, and with a view of the blue-marble Earth in the black sky that can be blocked out by a gloved thumb.



Solar Dynamics Observatory, ultraviolet image of the Sun, 2014
above: Sunlight in Space is uninterrupted and inexhaustible. Space resources developed in this century could enable unlimited, clean industrial energy and materials for human civilisation.

Apollo 17, Lunar Module window panorama of Old Family Mountain, North Massif, Taurus-Littrow, the Moon, 1972
opposite: The 'magnificent desolation' of the lunar landscape was created by billions of years of meteorite pulverisation. Only three days' travel from home, the Moon is the most likely first place for humankind to settle off-world.

Major government investments would also be required for this future. After routine heavy traffic between Earth and Moon, settlers would need technologies for the extraction of volatiles, metals, ceramics and glasses from the ground, manufacturing of usable products, lunar civil engineering, community-scale life support and food, and a broad spectrum of capabilities supporting day-to-day life. Growth would depend on a commercial economy of exporting rare minerals and tourism experiences. No appreciable government investments today are aimed at this vision.

Choosing Our Path

The US currently spends about $10 billion a year investing in space flight; the other spacefaring nations invest about as much altogether. This enormous sum is directed toward *exploring space*, with Mars as the vision. If sustained, by mid-century this investment could yield the astounding achievement of humans on an alien world more than 20 light minutes away. Alternatively, capitalism and the unique value of space resources might turn our space investment towards more tangible societal benefits. *Experiencing Space* and *exploiting Space* could become the vision. The prospect of *settling Space* someday tempts space architects with a tabula rasa for designing our built environment, the most fundamental opportunity since our profession began.[7] Someday, starting on the Moon, we may make a second home for humankind – and take our first steps towards inhabiting the infinite.

Notes

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Madhu Thangavelu

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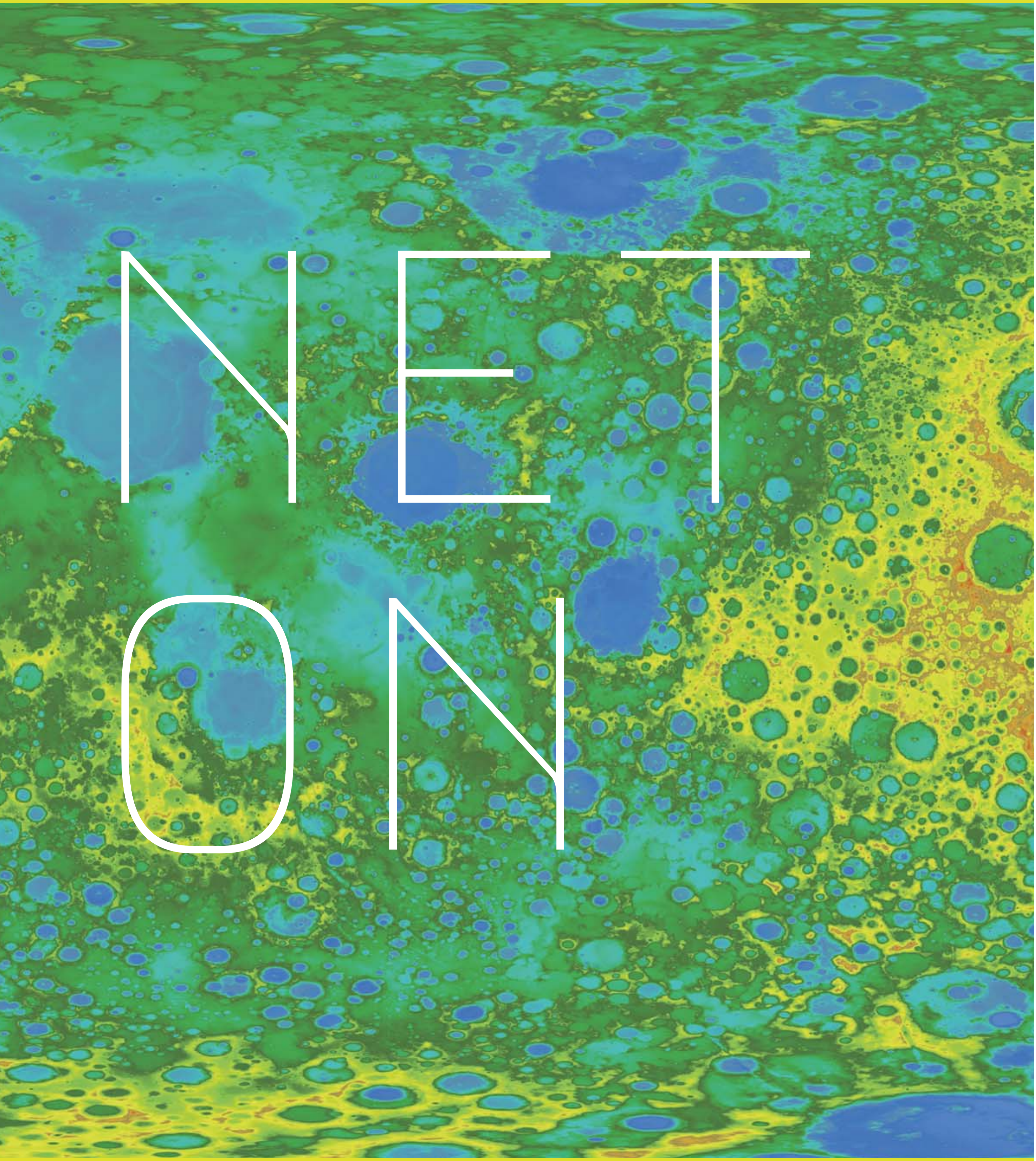
THE FUTURE OF ASTRONAUT

NASA Lunar Reconnaissance Orbiter (LRO) high-resolution lunar topography map, 2010

The Moon is being mapped in unprecedented detail by an armada of spacecraft from several nations. These recent false colour images are from the LRO, which is able to discern lunar features that are just 0.5 metres (1.6 feet) across.

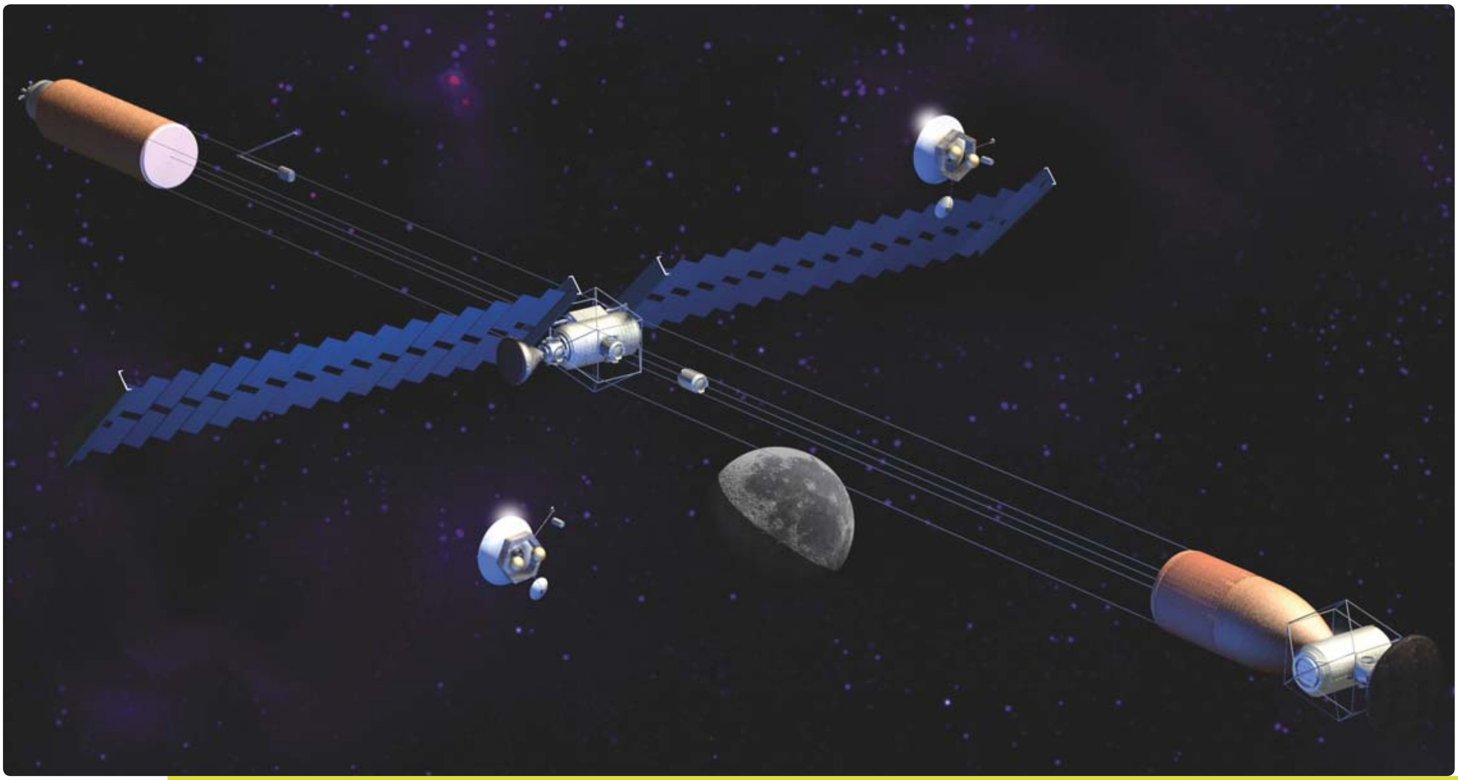


ACTIVITY AND SETTLEMENT

Ceaseless demographic growth and the depletion of the Earth's natural resources make the colonisation of space an increasingly compelling prospect. **Madhu Thangavelu**, an expert in the design of complex space projects, including space stations and exploratory missions, and a professor in the Department of Astronautical Engineering at the University of Southern California (USC), explores the possibilities and extreme environmental challenges posed by human settlement of our closest planetary neighbour, the Moon.

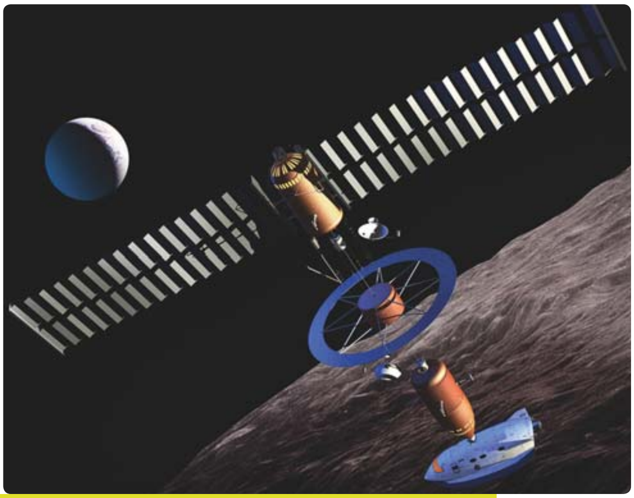
The Moon is our closest celestial neighbour, orbiting the Earth about a quarter of a million miles away. We have successfully conducted human exploration missions there. A new wave of spacecraft is currently providing new information in order to proceed with lunar development and settlement. Nations are preparing their own projects and programmes to return people to the Moon in longer missions, eventually leading to permanent settlements. All of which will involve advanced technologies and innovative methods in operations.

From the scientific viewpoint, the Moon offers a stable and protected platform from which to observe the celestial sphere, unhampered by the Earth's atmosphere or radio noise. Concepts suggesting harvesting solar energy on the Moon and beaming it back to the Earth could one day provide clean energy. The Moon, by virtue of its unique, pristine, untampered and desolate surface, is thought to hold a coherent record of solar activity over the past few billion years, and once unlocked will provide invaluable scientific information about solar system genesis, evolution and the future of planet Earth. Helium 3 on the lunar surface is more abundant than on Earth and could be harvested as future fuel for fusion reactors on Earth. The Moon, once populated by such facilities, will be maintained and evolved by crew. Eventually, a large population with diverse activities and interests, propelled by commerce and economic activity, as on Earth, may reside there in permanent settlements, giving rise to a bi-planetary civilisation.[1]



Buzz Aldrin, Madhu Thangavelu and Paul DiMare, Earth-Moon Cislunar Cycler, Department of Astronautical Engineering, School of Engineering and School of Architecture, University of Southern California (USC), Los Angeles, 2003

Lack of gravity is a critical concern in long-duration space flight, and crew may suffer permanent physiological impairment. Future earth-moon cycling spaceships in a tethered, spinning configuration could provide simulated gravity, and may evolve into vehicles for interplanetary expeditions.



Madhu Thangavelu and Paul DiMare, Lunar Polar Orbiting Hotel, Department of Astronautical Engineering, School of Engineering and School of Architecture, University of Southern California (USC), Los Angeles, 2007

A lunar polar orbiting hotel would be serviced by an earth-moon cycling shuttle. Such a facility would allow up to 60 lunar tourists to enjoy lunar vistas from an altitude of 100 kilometres (60 miles) as the Moon turns below them.

FUTURE SPACECRAFT MAY SIMULATE GRAVITY DURING TRANSIT, EMPLOYING CENTRIFUGAL FORCES BY SPINNING THE VEHICLE STACK AROUND ITS CENTRE OF MASS.

The Moon is the fifth largest satellite in our solar system. It is 3,476 kilometres (2,160 miles) in diameter and poses one-sixth the gravity of Earth. In a tidally locked orbit, the Moon always points the same face towards Earth. It has practically no atmosphere, and just 14.75 earth days of intense unfiltered sunlight, followed by a similar period of night-time. Its surface has an extreme environment, and therefore a lunar habitat will need to have substantial protection and should perhaps be located under the lunar surface, which is covered by a crusty rock layer called regolith. Without an atmospheric blanket, the Moon is constantly bombarded by meteorites. This continuous pummelling and tilling action on the regolith, referred to as 'gardening', along with severe diurnal thermal cycling, has created a fine, talc-like top layer of lunar dust, several inches deep in some regions, which is electro-statically charged through interaction with the solar wind and is very abrasive and clingy, fouling up spacesuits, vehicles and systems very quickly.

The Moon is seismically quiet and does not possess a magnetic field. The Sun, via solar flares and coronal mass ejections, causes frequent solar particle storms with potential lethal effect on crew, sometimes magnified several-fold when the Moon passes through the tail of the Earth's magnetic field. The lunar surface also experiences very large diurnal temperature swings. At the equator, the temperature varies from around 123ºC (253ºF) at noon to –233ºC (–387˚F) at predawn. With a spin-axis aligned nearly orthogonal to the ecliptic, the Moon has no seasons. Temperatures within permanently shadowed craters in the polar regions remain as low as –238˚C (–396˚F).[2] But for the surface of Venus in our solar system, Dante's vision of hell may well describe some of these extremes experienced on the Moon.

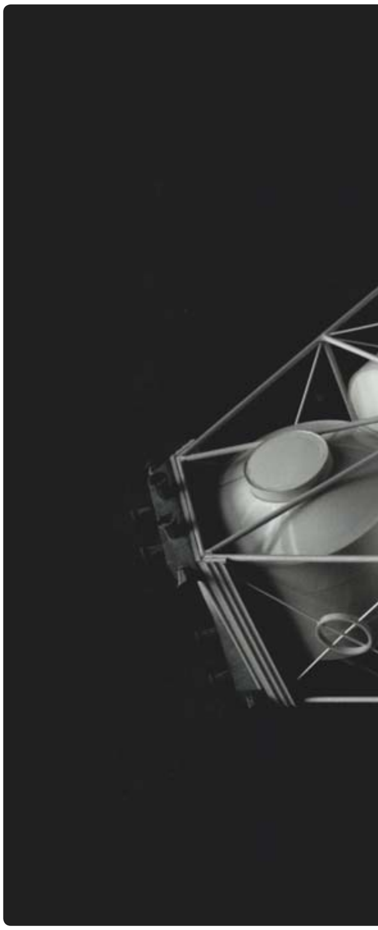
There is not a more environmentally unforgiving or harsher place to live than the Moon. And yet, since it is so close to the Earth, there is not a better place to learn how to live, away from planet Earth. If we can successfully manage to sustain human activity for long periods on the Moon, humanity will find it much easier to settle distant planets and prepare for voyages beyond our solar system, while enriching civil architecture here on Earth through advanced building technologies including the use of performant materials, energy-efficient design and innovative project execution that are derived from the hallmarks of good lunar space architecture.

Employing current technologies, spacecraft with astronauts take about three days to get to lunar orbit from Earth, quickly piercing through the intensely charged and deadly sheaths of the Earth's Van Allen radiation belts. Crewed spacecraft presently operate in zero gravity and most crew report space sickness during an adjustment period of two to three days. Future spacecraft may simulate gravity during transit, employing centrifugal forces by spinning the vehicle stack around its centre of mass. This strategy may solve some of the problems associated with this temporary, yet debilitating impairment.[3]

While scientific lunar exploration is the conventional rationale put forth by nations to go to the Moon, a new wave of concepts for lunar activity are being shaped around commerce, including lunar tourism. A 14-day lunar orbital tour might include a week-long stay in a lunar polar orbiting hotel, allowing passengers to see and appreciate all of the lunar landmarks in crisp close-up detail at a currently projected cost of $150 million per paying spacefarer.

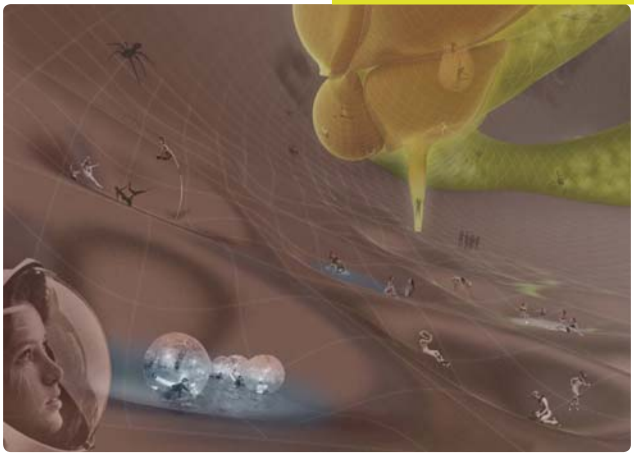
There are two schools of thought regarding lunar settlement build-up. One suggests that the initial settlement be built entirely using robots teleoperated from Earth, and the other proposes that crew be involved directly on site in the process. Perhaps a happy medium exists that employs astronaut crew in a strictly supervisory capacity, operating a variety of robotic assistants using teleoperations based on the lunar surface. Such an architecture would allow the crew to resolve anomalies swiftly, through extra-vehicular activity (EVA), if the need arises.[4]

Habitat structures on the Moon may be broadly classified as temporary and permanent structures. Initial visits will be conducted with temporary vessels like the Apollo lander. These structures, which fall in the pre-integrated class, arrive fully equipped and ready for human activity. No additional work is required before commencing mission operations. The Module Assembly in Low Earth Orbit (MALEO) lander concept developed by the School of Architecture at the University of Southern California (USC), Los Angeles (1988) is such a site office that has been proposed for the crew to live in while the lunar settlement infrastructure is being commissioned. As further settlement begins, visits will need larger lunar surface structures that require assembly on site using components flown in from Earth. These structures fall under the prefabricated, erectable class. Inflatable structures are currently thought to be good candidates to provide spacious volumes for crew during initial buildup activity.[5] After the first and second classes of temporary settlements have been deployed and utilised, the third class of structures that employ extensive use of local materials will be commissioned. These permanent lunar structures will perhaps be built deep under the lunar surface. Tools and heavy equipment will be flown as cargo from Earth to process lunar material in order to build large, spacious, permanent underground settlements on the Moon.



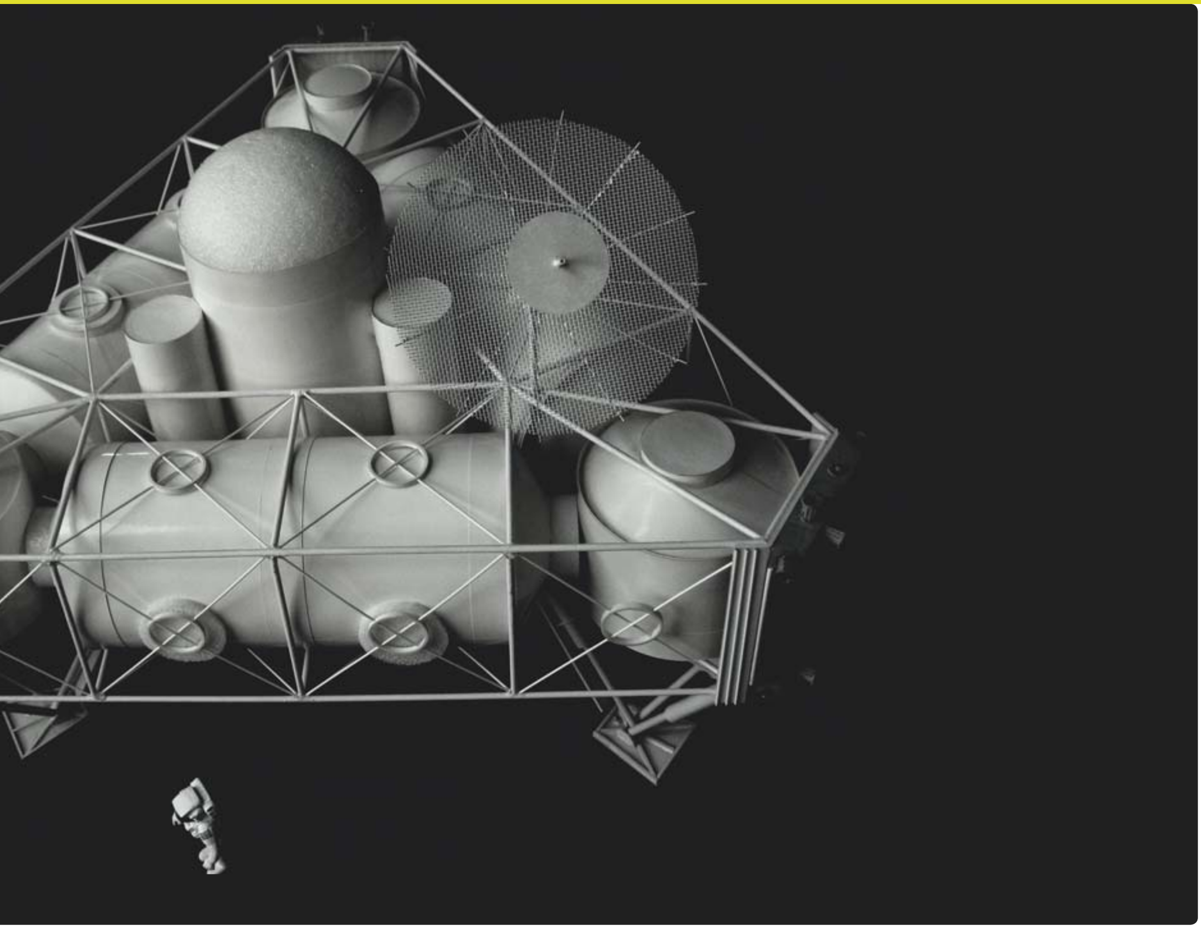
Lineweight Studio (Chienchuan Chen, Christine Chang, Haruka Horiuchi and Joy Wang), SHIFTboston Moon Capital Competition, 2010

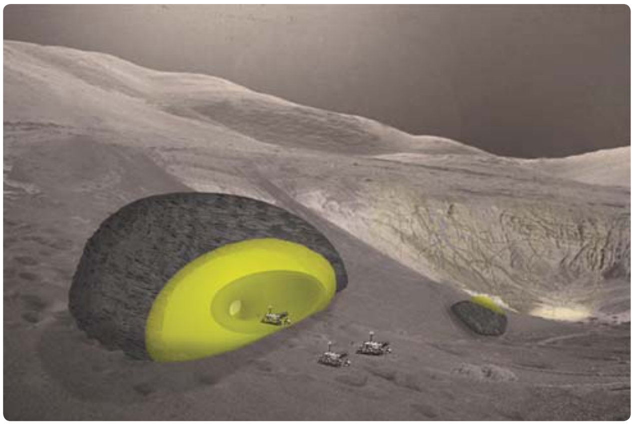
below and opposite bottom: Components shipped from Earth or prefabricated using in-situ resource utlisation (ISRU) on the lunar surface may be introduced into lunar lava tubes, and the permanent settlement may be built up, module by module, block by block, from materials brought from Earth or using local resources.



Madhu Thangavelu, Module Assembly in Low Earth Orbit (MALEO), School of Architecture and School of Engineering, University of Southern California (USC), Los Angeles, 1988

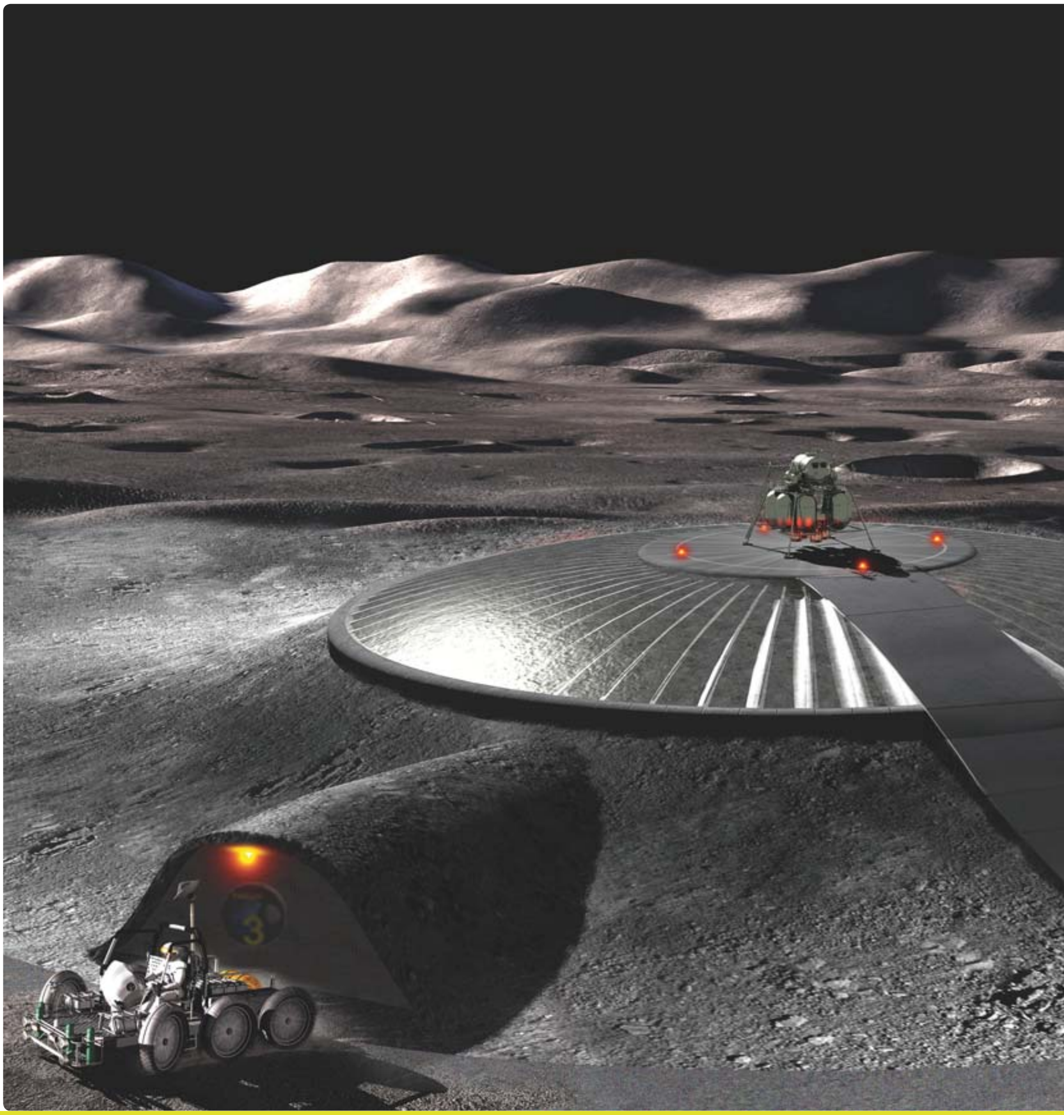
One way to circumvent the complexity of in-situ assembly and erection, and avoid the tools and systems needed to commission a base on the lunar surface, is to build the entire structure in low earth orbit using the International Space Station experience and technology heritage, and land the fully integrated facility at a predetermined location on the Moon.





Alternatively, large mobile bases have been proposed for initial exploration on a global scale. Such a strategy would allow the crew to perform more thorough and conclusive site investigations before settling on a permanent location to set up activities. The USC Nomad Explorer (1992) is such a candidate large mobile base. Mobile bases may also serve a variety of other functions such as helping to transport large cargo to remote locations and assisting lunar settlement assembly, as well as providing support for crew on long-distance traverses to remote locations on the Moon.

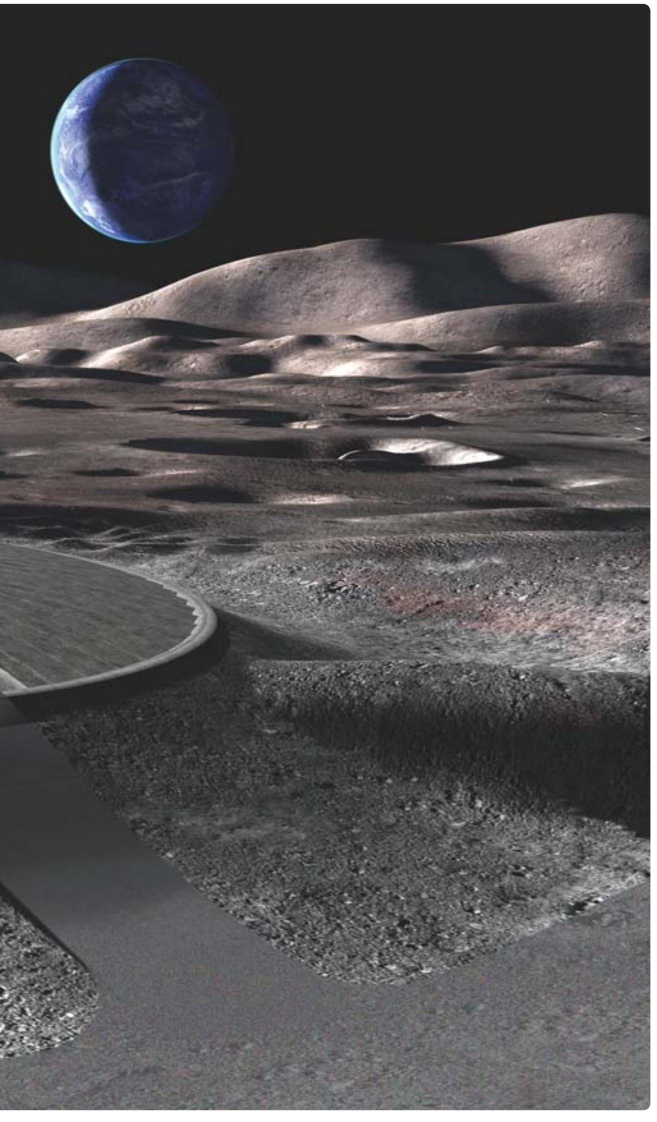
Temporary habitats for initial operations will be deployed quickly in the proximity of the lunar landers. Since several sorties are required, a critical infrastructure element is the lunar landing pad. A sturdy landing pad allows heavy landers to touch down repeatedly in the settlement vicinity without raising dust storms and throwing deadly hypersonic ejecta all around the landing area. Since the Moon has no atmosphere and very low gravity, such high-energy ejecta missiles can have lethal effects on crew and deployed surface assets over a radius of many kilometres.



Madhu Thangavelu and Paul DiMare, South Pole lunar landing pad, Shackleton Settlement, the Moon, Department of Astronautical Engineering, School of Engineering and School of Architecture, University of Southern California (USC), Los Angeles, 2012

A lunar lander capable of returning crew to Earth at short notice, should the need arise, set on a pad at a site in the lunar highlands near the south pole, a region that is currently under study as a viable spot to initiate permanent settlement activity.

THE USE OF ROCKS FOR BUILDING IS AN ANCIENT YET STURDY TECHNOLOGY, AND COULD BE USED EFFECTIVELY AND EXTENSIVELY IN PERMANENT LUNAR SETTLEMENT INFRASTRUCTURE DEVELOPMENT.



Current philosophy holds that in order to minimise the materials needed to be flown in, at great transportation cost, strategies that maximise the use of locally available resources must be adopted. This area of study is called in-situ resource utilisation, or ISRU.[6] The lunar surface is scattered with minerals and compounds that may be readily accessed to produce metals, glass, bricks, paints and other materials that are necessary for the construction of permanent settlements and infrastructure. Roads and landing pads, habitat platforms and shade walls may all be built from lunar rock and other ISRU materials. Accordingly, tools and robotic equipment such as excavators, graders, rock crushers and aggregate sorters could be flown in from Earth during the first phase of cargo missions. The use of rocks for building is an ancient yet sturdy technology, and could be used effectively and extensively in permanent lunar settlement infrastructure development.[7]

The Moon offers a variety of locations that may be naturally safer for human habitation. They include polar locations where the Sun shines throughout the year without setting, allowing the use of solar photovoltaics to generate power that is key to any sustained activity. The Malapert Mountain range and the Shackleton Crater at the south pole are regions where the Sun shines all year round, providing continuous access to solar energy. Certain 'peaks of eternal light' are known to exist there. We now know that these regions also have abundant deposits of water ice and volatiles. Lava tubes, those ancient, cavernous remnants of lunar volcanism, exist all over the Moon. They might offer voluminous spaces to build habitats. Lunar lava tubes are naturally protected from radiation and solar storms, as well as from meteorites and dust and debris associated with overflying service vehicles. If access to the interior of these lava tubes is feasible, these cavernous volumes might make ideal locations for permanent settlements. Habitats placed inside them will avoid the harsh lunar surface environment and the temperatures are expected to be steady around –20°C (–68°F). Recent data show that large pits, or 'skylights', exist all over the Moon that might be direct entry points into volcanic geological lava tubes.[8]

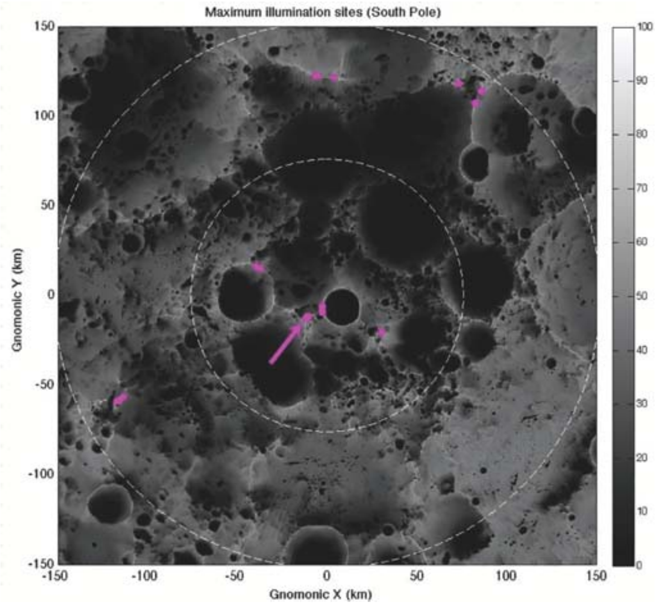
NASA and General Motors Desert Research and Technology Studies (D-RATS) team, Lunar Electric Rover (LER), 2010

A small pressurised prototype undergoing tests in the Arizona desert as part of the D-RATS programme.

In 2009, NASA's Lunar Reconnaissance Orbiter/Lunar CRater Observation and Sensing Satellite (LRO/LCROSS) mission directly verified the existence of water by sampling the plume of an impactor in the permanently shaded Cabeus Crater in the south polar region. The data indicated the presence of other volatiles and carbon compounds as well. If water is abundant, then water ice may be quarried and used for a variety of purposes including production of potable water, oxygen for atmosphere production and hydrogen for rocket fuel. If other volatiles are present in substantial quantity, as some of the data from recent analyses show, chemical compounds necessary for life sustenance, including agricultural fertiliser and hydrocarbons for a variety of uses, may be produced on site. Water would also make a good binding agent for making lunar concrete, allowing straightforward regolith stabilisation and dust suppression, for lunar development in permanently shadowed areas. Lunar sulphur has also been proposed as a binder.

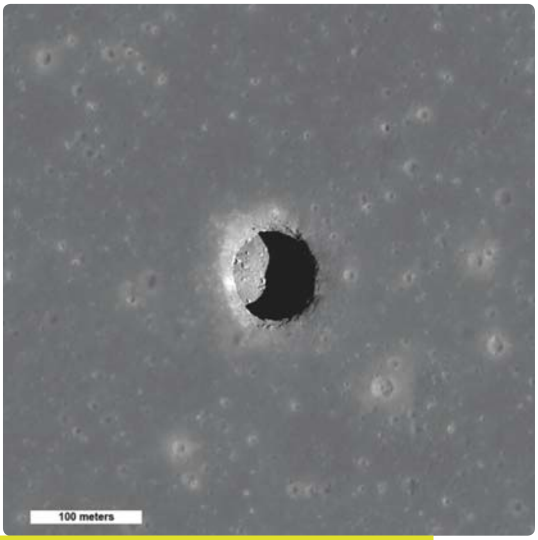
Evolving from technologies like Biosphere 2, already underway at remote locations such as the Antarctica base, fresh food production is a vital technology. The Crop Physiology Laboratory (CPL) at Utah State University, and the Controlled Environment Agriculture Center (CEAC) at the University of Arizona are leading the effort in this technology, which is critical for the sustenance of crew in permanent extraterrestrial settlements. The CEAC is currently supporting the Antarctica food production unit and the crew at CEAC are working on a new lunar greenhouse project.[9] Inhabitants of permanent lunar settlements will be nourished by fresh food grown on the Moon. Equally important, such a facility would be the keystone in our ability to close the loop in atmosphere regeneration and waste management. Concepts for lunar agriculture include burying large pressurised volumes and outfitting them for aeroponics, hydroponics and aquaponics.

EVOLVING FROM TECHNOLOGIES LIKE BIOSPHERE 2, ALREADY UNDERWAY AT REMOTE LOCATIONS SUCH AS THE ANTARCTICA BASE, FRESH FOOD PRODUCTION IS A VITAL TECHNOLOGY.



NASA, Lunar Reconnaissance Orbiter (LRO) peaks of eternal light, 2010

Highlighted spots in the lunar south polar region are where the Sun shines continuously throughout the lunar diurnal cycle for most of the year. The arrow points to a high-elevation ridge near the Shackleton Crater. Since energy is the key to development, early lunar settlements may begin activities around these spots.



NASA and Arizona State University, Lunar Reconnaissance Orbiter (LRO) lunar pits, 2010

Recently discovered lunar pits, commonly called 'skylights', photographed from the LRO now orbiting the Moon. Such features appear all over the Moon and may provide access into cavernous lunar lava tubes, several hundred metres across, which could be transformed into permanent habitats naturally protected from the extreme lunar surface environment.

The ultimate goal of astronaut space flight is to arrive safely, explore, discover and then settle other planets and satellites, initially in our solar system and eventually in extrasolar systems in humanity's quest to expand outwards from planet Earth, the cradle of humankind. The Moon, once portrayed as the ultimate 'high ground' to project the military might and defence capabilities of nation states, has now been transformed into the arena of choice for peaceful and progressive international collaboration and development via human space activity. The Moon beckons humanity towards a glorious future for all.[10]

Notes

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NASA and Heather Jones/Carnegie Mellon University, Lunar Reconnaissance Orbiter (LRO) images of Malapert Mountain range and Shackleton Crater, the Moon, 2014

High-resolution images of Malapert Mountain range (left) and the Shackleton Crater (right) are further enhanced using data from the LRO.

Architecture and Vision, MoonCapital, the Moon, 2010
The growing MoonCapital community with more interconnected domes.

Andreas Vogler

M O O N C

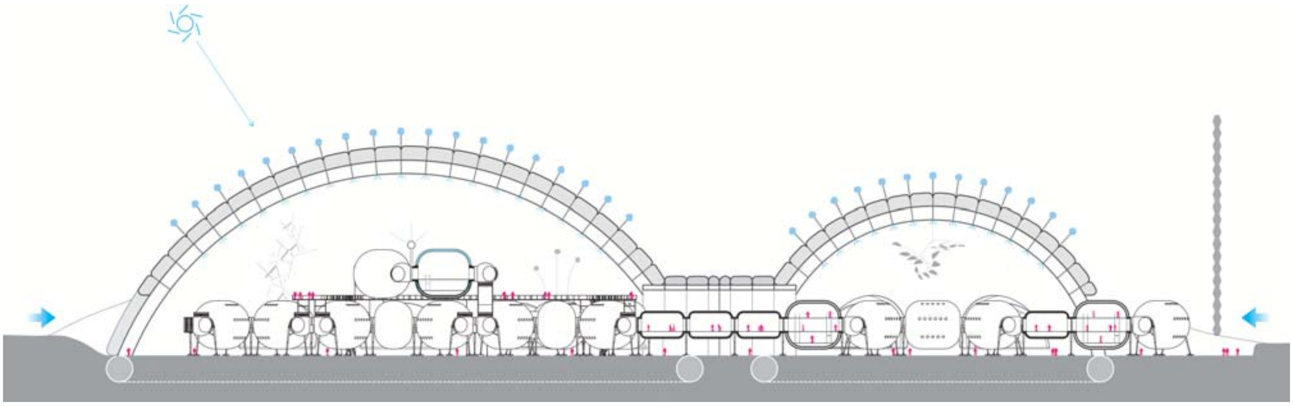
L I F E O N T H E M O O N 1 0 0

A P I T A L

Y E A R S A F T E R A P O L L O

Cross-section through the domes showing the interconnected inflatable modules inside standing on their own feet together with low-gravity sculptures to enrich the lunar landscape.

Munich-based architect **Andreas Vogler**, and co-founder of Architecture and Vision, here presents his speculative project MoonCapital, a proposal for habitation of the Moon in 2069, a century after the first lunar landing. Located in the most promising place on the planet for human settlement, the lunar south pole, MoonCapital accommodates 60 or so people in a series of modules, allowing for cellular growth.



MoonCapital is a design proposal for a second-generation habitation located on the rim of Shackleton Crater at the lunar south pole in the year 2069, 100 years after the first man arrived on the Moon. Based on current and anticipated technology and scientific knowledge, it develops a realistic scenario of how 60 and more people may live on the Moon 55 years from now.

In 2009, Architecture and Vision worked on a series of extraterrestrial habitats, such as the MoonVille project, to develop an architectural vision of a settlement on the Moon 40 years after the first moon landing. MoonVille was based on the concept that the limited amount of energy and resources on the Moon results in a defined size of settlement, similar to a medieval town, that corresponds to the amount of available farmland. In contrast to this, MoonCapital is investigating the principle of cellular growth based on a series of modules. The ongoing architectural research on how humans can not only survive but also live in Space is an important contribution to the scientific community.

The lunar south pole is the most promising location for a human settlement, since there are peaks of eternal light, breaking the lunar day/night cycle, which last 28 earth days. On the other hand, a cable lift leading down into the Shackleton Crater would allow the establishment of an astronomical research station with a large, deep-space telescope with absolutely no light pollution – a big step forward in the exploration of our universe. The impact of micrometeorites in the south pole is also less, and moonquakes, though there is not yet enough research on them in this location, are another issue to consider.

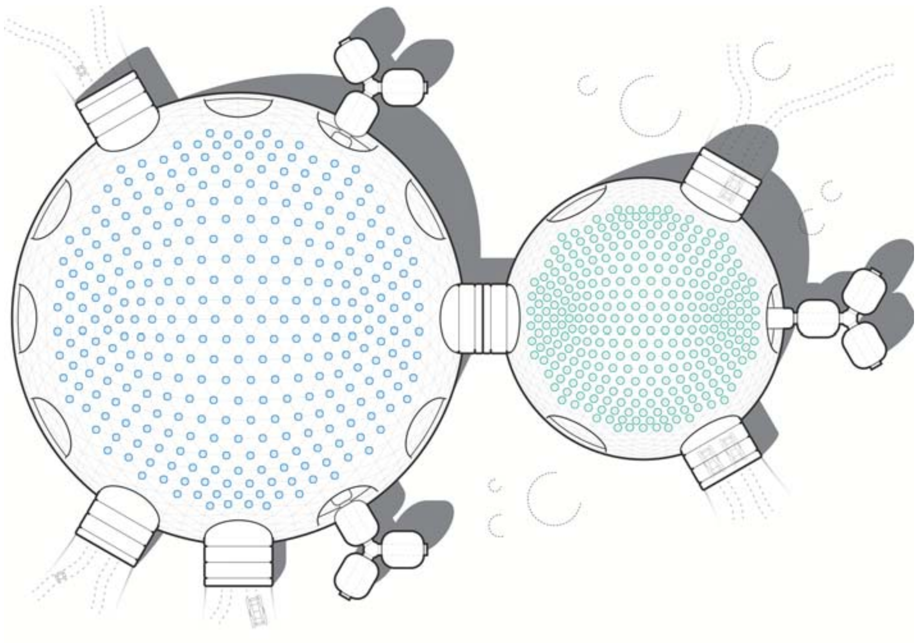
A Modular Community with Low-Gravity Sports and Sculpture

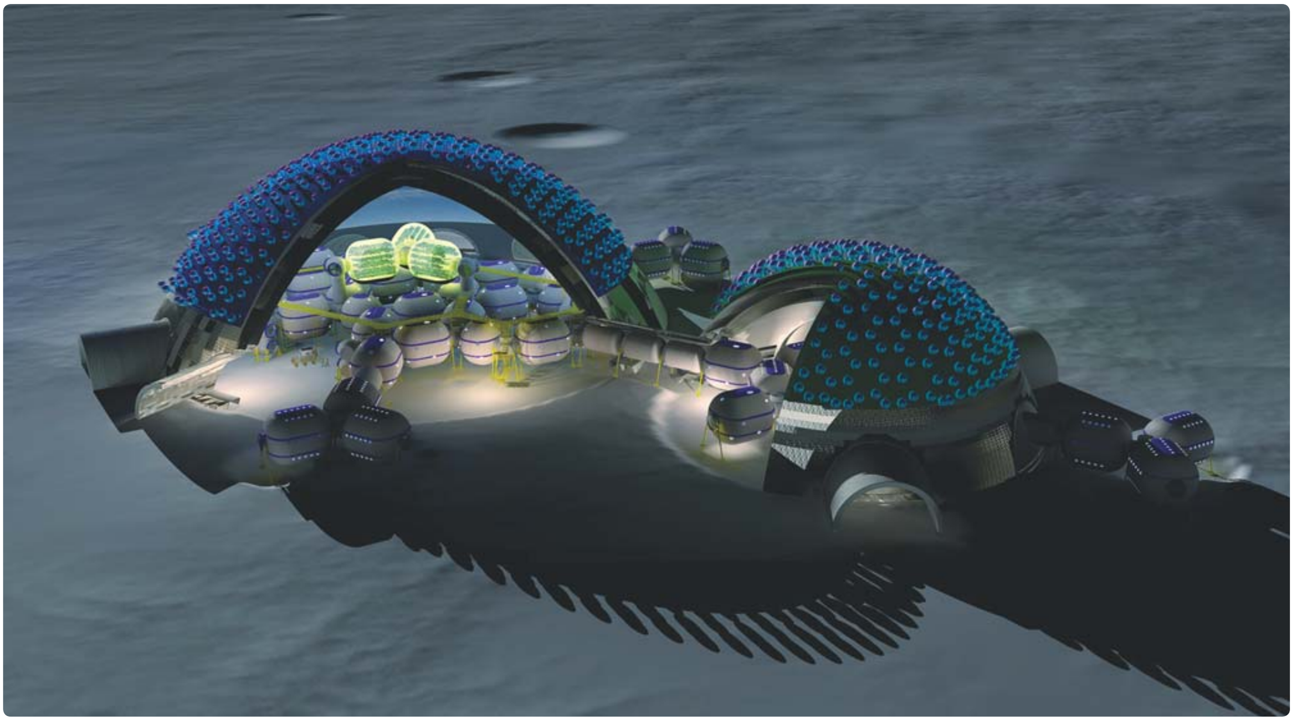
Radiation is posing one of the most severe problems of human space flight, and this has led to a proliferation of proposals for underground lunar habitations. The MoonCapital project, however, proposes the building of domes covered with lunar soil (regolith) as a controllable engineering solution that also allows humans a feeling of protected openness on the Moon's surface. The domes, over inflatable modules, form an intelligent skin, protecting from radiation and micrometeorites and allowing sunlight through a daylight-direction system inside. They are also a visible architectural testimony of human presence on the Moon. Built using inflatable and self-hardening concrete technologies, they are covered by a 3-metre (10-foot) thick layer of small regolith-filled sandbags, filled and mounted by small swarm robots, which also clear the site. Inflatable light receptors collect sunlight and direct it into the domes, where it can be used to translate the 28-day lunar day/night cycle into a 24-hour terrestrial day/night cycle. A digital projection allows artificial simulation of the Earth's skies on the surface of the domes, and can also play movies.

The smallest community and initial phase consists of two domes: a large one for the habitation and working modules, and a smaller one for the agriculture modules to produce food, and to recycle air and

top: View of the two base domes showing the rover ports and inflatable daylight collection system on top.

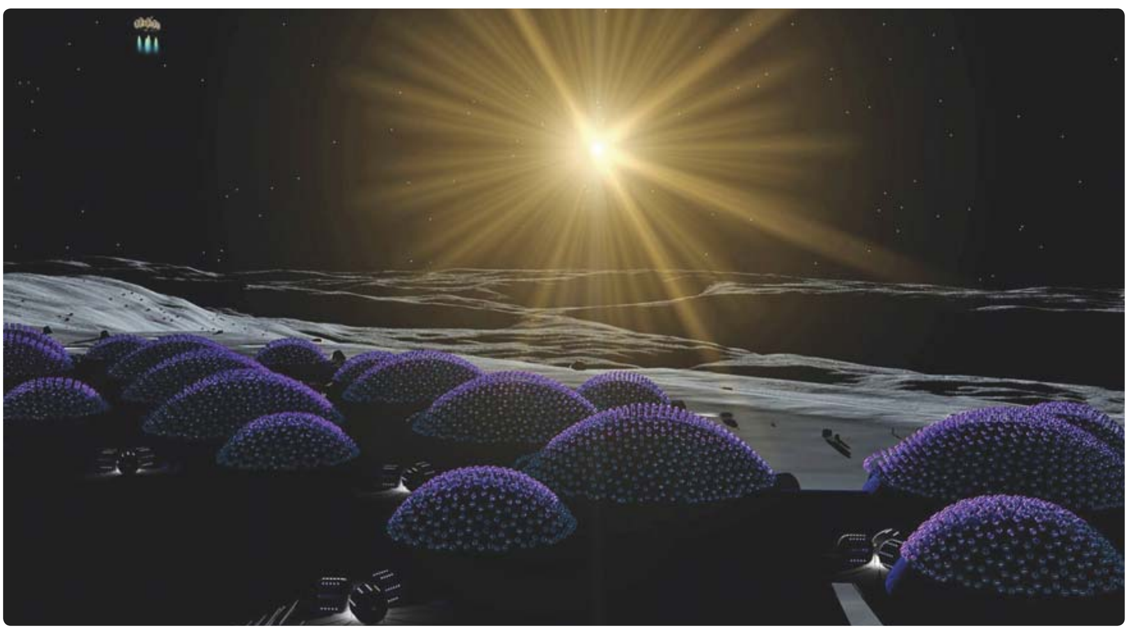
bottom: Cut-out rendering of the two base domes with the inflatable modules inside, and the three 'Paradise Modules' inside the large habitation dome.





top: Interior view of one of the large domes showing the interconnected working and habitation modules and the Paradise Modules above.

bottom: Evening atmosphere at the MoonCapital after a long lunar day, which lasts 14 earth days.



MOONCAPITAL'S DIRECTIVE IS HUMAN-CENTRED: THE INTERIOR PLANNING OF THE MODULES IS DEFINED BY SAFETY, SOCIAL BEHAVIOUR AND PSYCHOLOGICAL NEEDS.

water. The modular system allows growth and extension as the new lunar society develops. MoonCapital contains facilities for research, production and leisure, and a small hotel for visitors. Spaces inside the domes not occupied by pressurised modules are used for rover docking and maintenance, radiation-protected surface science, and low-gravity spacesuit sports like moon soccer and moon tennis. Sculptures will be installed in the vacuum environment to fulfil inhabitants' desire for culture, but also to aesthetically explore this fascinating environment.

The inflatable modules are designed to fit into a 6-metre (20-foot) diameter rocket fairing, leaving many options open for future launch capabilities. They have a deployed diameter of 11 metres (36 feet) and three levels. Main circulation is on level 0, from where levels –1 below and +1 above can be accessed. The modules are connected by rigid carbon-fibre nodes that allow three horizontal and two vertical connections, and also contain noisy equipment such as life support. The modules have windows to allow views outside into the dome, and virtual windows that allow a radiation-protected view onto the lunar landscape.

Vertical circulation is realised by muscle-powered lifts and staircases. Ceiling height is kept between 2.4 and 2.6 metres (7.9 and 8.5 feet), and uses soft padding as it is easy to reach this height by jumping in one-sixth of the Earth's gravity. For the rather compact spaces, a low ceiling height is beneficial for the perceived spatial proportions and keeps the pressurised volume low as well as the environmentally controlled volume. However, the arrangement also provides large spaces for gymnastics, reaching up to 6 metres (20 feet) ceiling height, in which to enjoy and explore the low gravity.

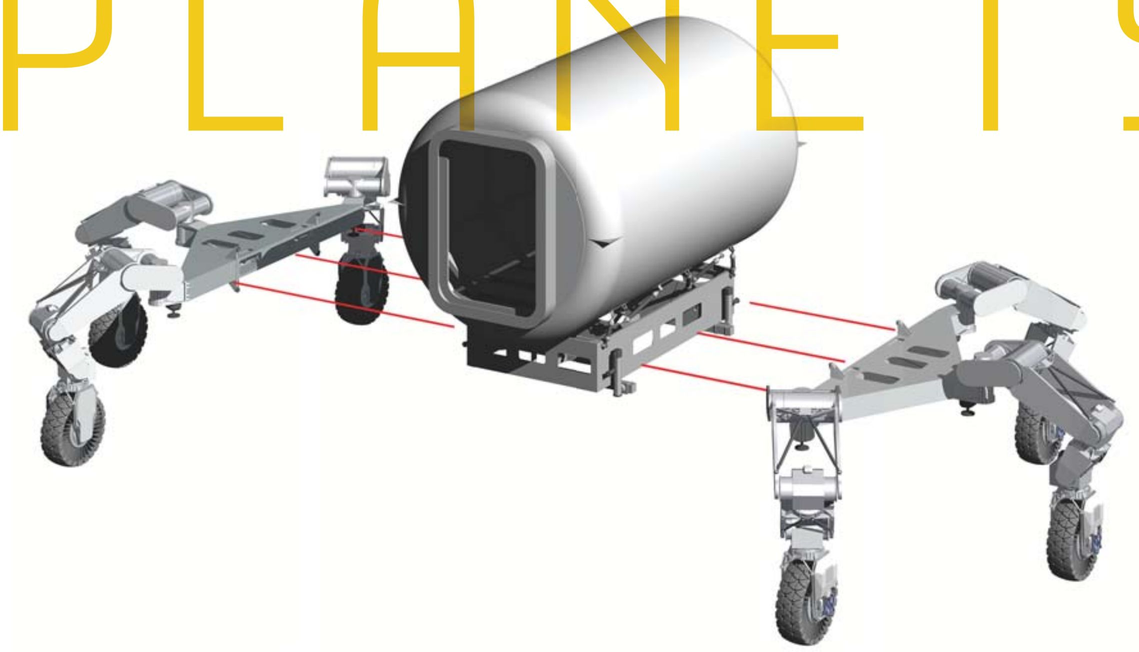
A Stimulating Interior in a Monotonous Exterior

MoonCapital's directive is human-centred: the interior planning of the modules is defined by safety, social behaviour and psychological needs. However, in reality a moon habitation is more a machine than a living environment as we know it on Earth, and space architects therefore need to consider human needs even more carefully. MoonCapital creates and respects private, semi-private, semi-public and public spaces to allow individuals maximum personal freedom in a confined environment. Sensory deprivation is also a main concern where the sky is always black and going out to 'breathe some fresh air' is impossible: environmental control (temperature, humidity, pressure, illumination, olfactory), communication, audio systems and food are all employed as stimulating countermeasures to this. A combination of sensors and algorithms can individually react on the people and expose them to the unexpected. Surfaces, decor, artwork and interactive devices such as electronic sculptures can further enrich daily life on the Moon.

Module Eden: The Lunar Paradise

In the larger habitation and working dome of MoonCapital's initial phase, three 'Paradise Modules', or Module Eden One to Three, have a normal earth atmosphere and contain aeroponic plants such as strawberries and apples that are in blossom over the year and bear sweet fruits and berries. These modules differ from the purely food-producing, robot-controlled agricultural modules: butterflies and birds fill them with movement and natural sounds, tables and benches allow people to meet there, to relax or just look at the plants, hear the birds and smell the air, creating a public park for the lunar inhabitants. The transparent skins also illuminate the dome and can be seen from the windows of other modules. Module Eden forms the green heart of the MoonCapital and a connection with home, the planet Earth, casting its blue light into the black Moon sky. AD

ARCHITE FOR OTH PLANETS



Opportunities for Space Architecture are proliferating over time. As NASA architect and robotics engineer **A Scott Howe**, however, explains, a varied skill set is required to develop the right specialist expertise to become a space architect. Extreme environmental factors always have to be taken into consideration when designing for Space. These vary from lack of gravity, extreme variations in temperature and exposure to abrasive materials, such as lunar dust. Architects also need to develop an acute awareness of transportation systems and robotic constructions. It is, though, only with prototyping that designs, systems and materials can start to be tested.

CTURE ER

A Scott Howe

NASA space architects get a chance to design and build off-the-grid prototypes that help increase our knowledge of what future space structures will be like.[1] With improvements in propulsion and lowering of launch costs, it is only a matter of time before opportunities to build in Space and on other planets will abound.

Challenges and Constraints

Assuming comfort for the occupants, environmental conditions drive architectural design. In Space the same conditions become more extreme, and there are additional constraints.[2] Space architects divide environments into two major categories: zero gravity (in orbit away from a planet outside the atmosphere) and planetary surface. For zero-gravity environments,[3] the external temperature of a structure can vary 360˚C (680˚F) between the solar-illuminated and shaded sides, which could rip the structure apart with expansion and contraction if the wrong materials are chosen. In Space structures also need to be shielded from deadly solar particle events (SPEs), where energetic particles are ejected from the Sun, and galactic cosmic rays (GCRs) that cause constant radiation from all directions. Other environmental dangers include pressure differences, micrometeoroid impacts, free radical oxygen and lack of gravity.

Lack of gravity may not always be as liberating as it seems. Large volumes in zero gravity can pose a very difficult set of challenges due to the lack of convection and air movement. Carbon dioxide, nitrogen or other gasses could accumulate in dangerous pockets. And if a crewmember somehow lets go and drifts away at a very slow rate of speed, it could take a week for him or her to drift across the volume – without access to food, toilet facilities or other amenities.

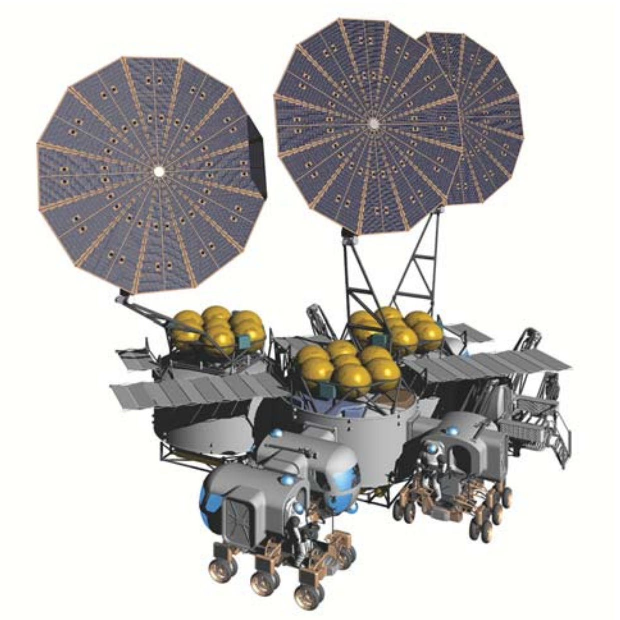
Planetary surfaces[4] such as the Moon or Mars have partial gravity, but present other issues such as dust. Dust on the Moon is an abrasive fine powder that sticks to everything, gets into machinery, and could be carried inside the habitat on boots and environmental suits, posing a health hazard. Some planets may also have corrosive atmospheres or extreme temperatures.

Transportation

Space architects must not only know the mass of all the materials needed to construct their building; they must also be aware of the nature of the transportation system before they even begin the design. This is like knowing

NASA Jet Propulsion Laboratory, All-Terrain Hex_Limbed Extra-Terrestrial Explorer (ATHLETE), 2009
Robotic construction demonstration docking habitats using remote control. Three-limbed 'Tri-ATHLETE' vehicles (opposite) carry the habitat to the target location, then undock and go back to get another load. Construction can be accomplished robotically by docking modules together (above).

right: The mobility system unloading a habitat mockup.



Kriss Kennedy, Larry Toups (NASA Johnson Space Center) and A Scott Howe (NASA Jet Propulsion Laboratory), Conceptual design for a permanent lunar outpost, 2009
top: The outpost uses three vertical cylinder habitat modules and pressurised rovers.

A Scott Howe (NASA Jet Propulsion Laboratory), Habitable volume, 2009
above: The habitable volume can be expanded using deployable pressurised sections, such as inflatable domes with kit-of-parts partition systems (left). Docking multiple modules together provides for future growth (right).

NASA Jet Propulsion Laboratory, All-Terrain Hex_Limbed Extra-Terrestrial Explorer (ATHLETE) sortie mission, 2009
below: Habitation modules can be carried away by ATHLETE to follow small pressurised rovers for long-distance sortie missions away from the main outpost (a 'motorhome-jeep' concept).

that all the building materials, construction equipment, power-generation capability, fuel, air to breathe, water, gases, kitchen, food, clothes, medical equipment, construction equipment and workforce must fit on only one truck. With such a requirement, space architects must be very clever in their use of deployable mechanisms, kit-of-parts concepts and lightweight materials. If possible, in-situ resource utilisation (ISRU) should be adopted to avoid materials taking up precious volume and mass in the package that must be lifted out of Earth's gravity well.

Every aspect of material handling must be part of the design process, right down to how a habitat will be lifted off the top of a lander (a rocket-powered cargo ship) and placed down on the surface. The chances are that a crew member may not be available during construction, so everything must be robotically controlled.

Robotic Construction

Astronauts are expensive labour. They require a pressurised cabin to live in, and all of the equipment needed for habitation is quite heavy and costly to lift out of Earth's gravity well and maintain in a harsh environment. It is therefore much cheaper to send machines[5] ahead to build the structures humans will occupy. Robotic construction systems could consist of autonomous assemblers that put together modules and trusses, or self-assembling systems where all of the components are robotic. When everything checks out and the habitat is operational, the crew can be sent to work on more important things, such as exploration.

Planetary Outposts

NASA's design for a lunar planetary outpost[6] as part of the 2009 Constellation Program included transportation, robotic construction,[7] and local mobility. The outpost design followed all the rules of function, ergonomics, egress and habitability that earth architects follow, packaged into compact, lightweight deployable structures that were required to 'live off the land' in a remote environment.

The modular construction of the outpost included lightweight pressure vessels to contain 55kPa (8 psi) cabin pressure in lunar vacuum, with inflatable sections that could expand during construction. Later, when crew members arrived, they could snap together kit-of-parts partition systems inside the volume. Modules could be docked together for future expansion of the outpost, and could be carried away from the outpost for week-long sorties.

Functional Prototype

In 2010–12, an off-the-grid prototype of part of the lunar outpost was constructed that could be tested in extreme conditions on Earth. The Habitat Demonstration Unit (HDU)[8] was tested for several years in the Arizona desert, in a location that had similar geological features to those that might be found on the lunar surface. The prototype was fairly high fidelity, with operational software, workstations, airlock, deployable deck and trained astronaut crew.

Though the HDU has not yet been built in Space, such earth-based analogues are bringing NASA much closer to understanding how real space habitats may look and function. Eventually, when humans begin to move away from Earth, we will not have access to hardware stores or timber yards – we will have to live off the land and produce our own energy, even when the environment is total vacuum or low gravity. The work space architects are doing with the HDU and other prototypes will give space crews the necessary skills when the time comes to make the move. Off-the-grid technology developed by NASA could also eventually trickle down to influence architecture in extreme or remote locations on Earth. D

The research described in this article was carried out at the National Aeronautics and Space Administration (NASA) and the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

Notes

1. Kriss Kennedy, 'Vernacular of Space Architecture', in A Scott Howe and Brent Sherwood (eds), *Out of This World: The New Field of Space Architecture*, American Institute of Aeronautics and Astronautics (Reston, VA), 2009, pp 7–21.
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4. Brent Sherwood and Larry Toups, 'Design Constraints for Planet Surface Architecture', in Howe and Sherwood, op cit, pp 171–8.
5. A Scott Howe and Silvano Colombano, 'The Challenge of Space Infrastructure Construction', *Proceedings of the AIAA Space 2010 Conference and Exposition* (Anaheim, CA), American Institute of Aeronautics and Astronautics (Reston, VA), 2010.
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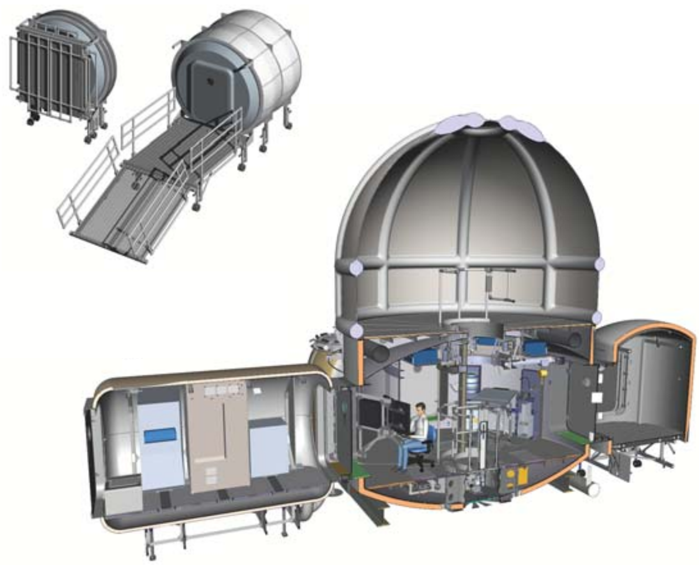
7. Brian Wilcox, Todd Litwin, Jeff Biesiadecki, Jared Matthews, Matt Heverly, Julie Townsend, Norman Ahmad, Allen Sirota and Brian K Cooper, 'ATHLETE: A Cargo Handling and Manipulation Robot for the Moon', *Journal of Field Robotics*, 24 (5), 2007, pp 421–34.
8. A Scott Howe, Kriss Kennedy and Tracy Gill et al, 'NASA Habitat Demonstration Unit (HDU) Deep Space Habitat Analog', *Proceedings of AIAA Space 2013 Conference and Exposition* (San Diego, CA), 2013.



Kriss Kennedy, Larry Toups (NASA Johnson Space Center) and A Scott Howe (NASA Jet Propulsion Laboratory), Habitat Demonstration Unit (HDU), 2011
above: HDU section through laboratory, hygiene module, airlock, and habitation dome. The detail of an inflatable version of the airlock (upper left) shows how structures can be compactly stowed and deployed when needed.

right: HDU interior showing workstations around the perimeter. A central lift performs dual purpose to access the 'atrium' plant growth system between floors using red-blue light optimised for plants.

far right: The HDU during mission testing in the Arizona desert.

Neil Leach

BUZZ ALDRIN

Buzz Aldrin on the Sea of Tranquility, 21 July 1969
One of the most iconic images from the Apollo 11 mission.

Buzz Aldrin's boot print on the Moon, 21 July 1969
Buzz Aldrin took this now famous photograph of his boot print on the Moon.

MISSION TO MARS

Buzz Aldrin is a former astronaut and the second man to walk on the Moon. On 21 July 1969 he followed the late Neil Armstrong down the ladder from the Lunar Module Eagle on to the surface of the Moon after Armstrong had uttered his now famous words: 'This is one small step for [a] man, one giant leap for mankind.' In so doing they realised the commitment made by President JF Kennedy in 1961 in a speech in front of the American congress to send a man to the Moon and bring him back safely before the decade was out. Aldrin will always be known primarily for this exploit. Nor do those brief precious moments ever fully leave him: 'Whenever I gaze at the moon, I feel like I'm in a time machine. I am back to that precious pinpoint in time, nearly 45 years ago, when Neil and I stood on the forbidding, yet beautiful, Sea of Tranquility.'[1]

Above all, Aldrin is an all-American hero. Since those heady days in 1969, nothing has been quite the same for him. A school has been named after him; Buzz Lightyear of *Toy Story* (1995) was reportedly named after him; and he has even appeared on *The Simpsons* and a reality television show, *Dancing with the Stars*. And yet, despite everything, Aldrin maintains an active interest in Space. As an octogenarian, he is still broadcasting his ideas. Given his background and his name, whatever he says or writes therefore needs to be taken seriously. Aldrin's latest book, *Mission to Mars: My Vision for Space Exploration* (2013), plots out the next step in his vision for space exploration.[2]

The book consists of several sections in which Aldrin refers to some of the key challenges that the future of space exploration is addressing, including colonising the Moon, space tourism and harnessing energy from extraterrestrial environments. It is clear, however, that all this is but a prelude to the main topic, and the title of the book itself – *Mission to Mars*. As Aldrin puts it, 'Mars simply tops the list of future destinations to explore'.[3] Given his own personal history, we could easily imagine him making an impassioned plea to return to the moon some 40 years after the historic Apollo 11 mission. But instead Aldrin sets out his vision for a mission to Mars. So why would a man who made his name by walking on the Moon advocate going to Mars instead? The answer, for Aldrin, is simple:

> Let me be upfront on this point. A second race to the moon is a dead end, a waste of precious resources, a cup that holds neither national glory nor a uniquely

The lunar landings in 1969 provided the watershed moment for space exploration, bringing the celestial into direct physical contact with man for the first time. As the second man to walk on the Moon, Buzz Aldrin maintains a unique place in American and space history. Here, Guest-Editor **Neil Leach** looks at why Aldrin has chosen to highlight the potential of Mars over the Moon in his recent book, *Mission to Mars: My Vision for Space Exploration* (2013).

Buzz Aldrin in the Apollo 11 Lunar Module Eagle, 20 July 1969
below top: Aldrin photographed by astronaut Neil Armstrong.

Buzz Aldrin, University of Southern California (USC), Los Angeles, 2012
below bottom: Aldrin giving a lecture to students from the Astronautics and Space Technology Division of the USC Viterbi School of Engineering about his vision for a mission to Mars.

> American payoff in either commercial or scientific terms. How do we frame our collaborative or international effort to get to the moon again? Let me emphasize: Certainly *not* as a competition. We have done that, and to restart that engine is to rerun a race that we won. Let's take a pass on that one. Do not put NASA astronauts on the moon. They have other places to go.[4]

Aldrin's vision for Mars entails adopting a 'cycler' system that maintains a spaceship in constant cycling orbit: 'Central to this idea is using the relative gravitational forces of Earth and the moon to sustain the orbit, thereby expending little fuel.'[5] Another key concept is to establish initial bases on one of the planet's two moons, Phobos or Deimos. These will serve as 'offshore islands' for the eventual push for Mars itself.[6] Their low gravity will allow them to serve as staging posts from which to launch flights to Mars, and they are close enough to allow for telecontrol of robotic equipment on the surface of Mars, before the eventual actual landing of humans.

For architects, it is perhaps the final chapter, 'Homesteading the Red Planet', of Aldrin's book that is likely to prove the most interesting. For Aldrin, any mission to Mars needs to be significantly different to the Apollo missions:

> We need to start thinking about building presence on the red planet, and what it takes to do that. I feel strongly about this. This is an entirely different mission than just putting people on the surface of that planet, claiming success, having them set up some experiments and plant a flag, to be followed by quickly bringing the crew back to Earth, as was done in the Apollo program.[7]

He sees a mission to Mars as ultimately about setting up a permanent human presence on the red planet. It involves colonising Mars with all the architecture and engineering infrastructure that such a project entails. Moreover, it is important that humans do go there, in that humans have many advantages over mere robots. They are faster, more efficient, more nimble, and can evaluate any situation in real time. But at the same time there are real challenges to sending humans to Mars, not least that of bringing them back again. Moreover, as Aldrin notes: 'Agriculture under extreme conditions, power generation, radiation protection, and

Humans on Mars
An artist's impression of a future Mars mission.

advanced life-support systems are called for.'[8] There are also dangers for Mars itself, should early explorers unleash microbes from Earth, and inadvertently contaminate the environment.

Aldrin's vision for the colonisation of Mars includes in-situ resource utilisation (ISRU) – the necessity of making full use of local materials: 'Some locally derived materials on Mars have been singled out for initial settlement construction, like fiberglass, metals and masonry, either for unpressurized shelter or covered with Martian regolith to hold the pressurized volume. Polyurethane and other polymers can be made from ethylene extracted from Mars's carbon dioxide-rich atmosphere.'[9] He sees the need also to fabricate hydroponic growth labs for cultivating vegetables, and terraforming the Martian landscape so as to make it 'a less hostile, highly livable place for humans and to support homesteading the planet'.[10]

But how exactly is this to happen? In the book, Aldrin imagines the possibility of a US president marking the 50th anniversary of Apollo 11's landing on the Moon, in 2019, and taking the opportunity to deliver an impassioned speech that more fully echoes President Kennedy's earlier pledge: 'I believe that this nation should commit itself, within two decades, to establish permanence on the

DURING THE COLD WAR IT WAS CLEAR THAT THE SPACE RACE SERVED AS A VICARIOUS DISPLACEMENT FOR OTHER CONCERNS, FUELLED AS IT WAS BY RIVALRY AND NATIONAL PRIDE. THE QUESTION THAT REMAINS IS WHICH NATION NOW NEEDS TO EXPLORE SPACE MOST.

Homesteading the Red Planet
An artist's impression of what a 'terraformed' Martian landscape might look like.

planet Mars.'[11] Making that declaration, Aldrin notes, will be predicated on answering a set of questions: 'America, do you still dream great dreams? Do you still believe in yourself? Are you ready for a great national challenge? I call upon our next generation of space explorers – and our political leaders – to give the affirmative answer: Yes!'[12]

Indeed, in 2010 President Obama did make a statement about going to Mars that echoed that of President Kennedy: 'By the mid-2030s, I believe that we can send humans to orbit Mars and return them safely to Earth. And a landing on Mars will follow. And I expect to be around to see it.'[13] Importantly, however, these words were not backed up by any real commitment to actually seek funding for this objective. There is a significant difference between believing something possible and fully committing oneself to that goal. If one is looking for a commitment to actually go to Mars, instead of looking to the public sector we might look to the private sector, and in particular to Elon Musk, the ambitious entrepreneur who made a substantial fortune through his development of PayPal, and who now heads up the Space Exploration Technologies Corporation (SpaceX) initiative that already has advanced plans to land on the Red Planet (see pp 66–7).

During the Cold War it was clear that the Space Race served as a vicarious displacement for other concerns, fuelled as it was by rivalry and national pride. The question that remains is which nation now *needs* to explore Space most. Does the US as a nation have the same motivation today? It is perhaps more likely that other nations with more to prove – such as China – will seize the initiative. A Chinese astronaut on the surface of the Moon will have an impact not so dissimilar to Beijing hosting the 2008 Olympic Games. China has arrived as a major economic force; it is on the ascendancy and has every reason to look to Space as an arena in which to express it.

Even Aldrin seems to recognise this: 'China has already set in motion its human spaceflight program, methodically leading to modular buildup of an independent space station program and robotic lunar exploration, and seems intent on dotting the moon's surface with footprints of Chinese astronauts.'[14] Despite his unfettered enthusiasm for an American mission to Mars, one is left wondering whether it might just be a Chinese mission that gets there first.

Notes

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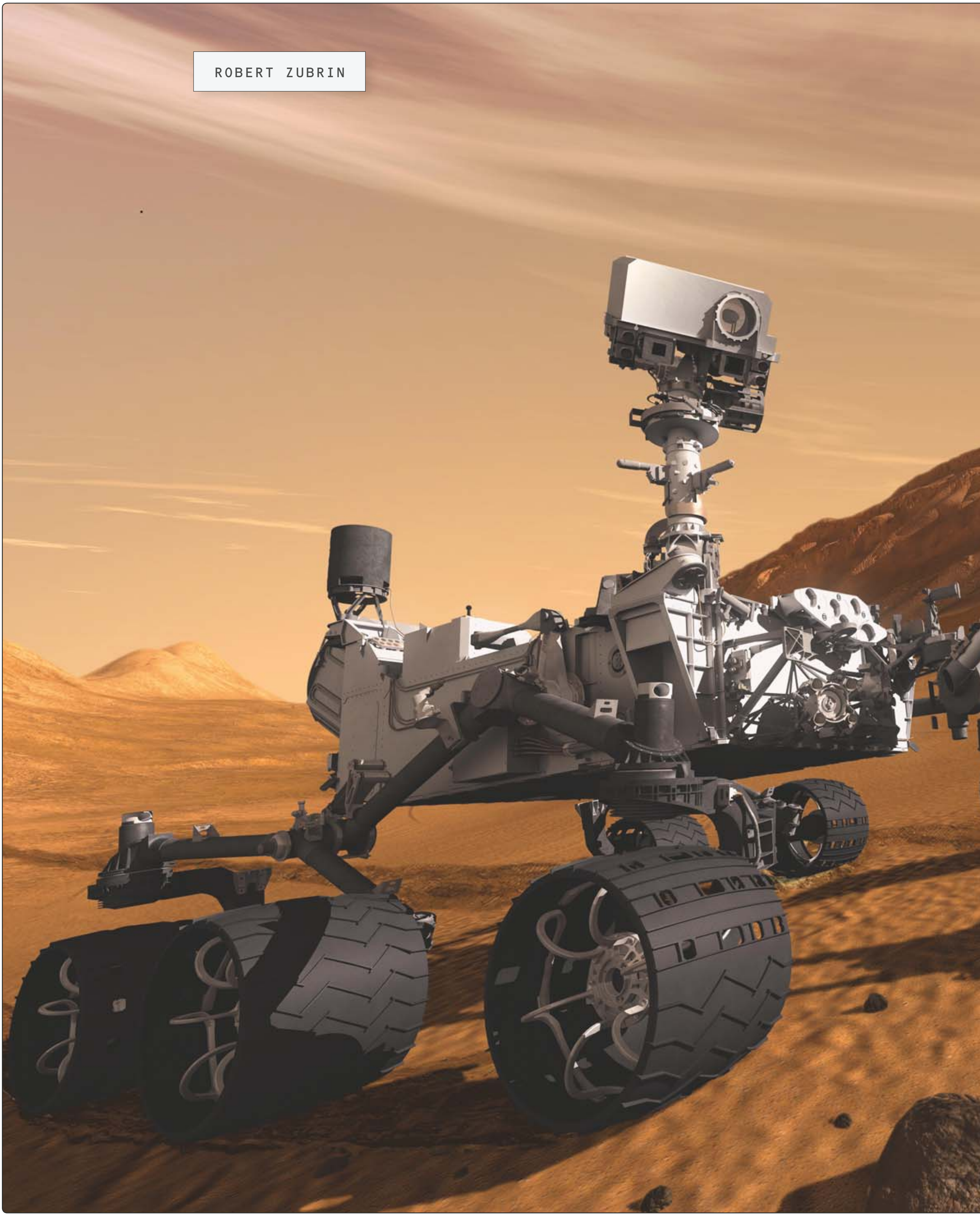
ROBERT ZUBRIN



COLONISING THE RED PLANET

HUMANS TO MARS IN OUR TIME

Astronautical engineer and President of the Mars Society **Robert Zubrin** explains why a human exploration of Mars is preferable to the Moon and now within our grasp, despite being an average of 225 million miles away. He advocates how missions might be realised through a Mars Direct approach that employs relatively small spacecraft launched directly to the Red Planet via boosters.

NASA, CURIOSITY MARS ROVER, 2012
Artist's concept. While packing 10 times the payload of Opportunity, Curiosity's average speed is still less than 30 metres (100 feet) per hour, and it cannot dig, drill or do any of the lab analysis required to discover or characterise life on Mars.

Many people believe that a human mission to Mars is a venture for the far future, a task for 'the next generation'. Such a point of view has no basis in fact. On the contrary, the US has in hand, today, all the technologies required for undertaking an aggressive, continuing programme of human Mars exploration, with the first piloted mission reaching the Red Planet within a decade. We do not need to build giant spaceships embodying futuristic propulsion technologies in order to go to Mars. We do not need to build a lunar base, a grander space station, or seek any other way to mark time for further decades. We can reach the Red Planet with relatively small spacecraft launched directly to Mars by boosters embodying comparable technology as that which carried astronauts to the Moon almost a half century ago. The key to success comes from following a 'travel light and live off the land' strategy that has well served explorers over the centuries that humanity has wandered and searched the globe. A plan that approaches human missions to the Red Planet in this way is known as the Mars Direct approach.[1] Here is how it would work.

The Mission

At an early launch opportunity, for example 2022, a single heavy lift booster with a capability equal to that of the Saturn V used during the Apollo programme (1967–72) is launched off Cape Canaveral and uses its upper stage to throw a 40-tonne unmanned payload onto a trajectory to Mars. Arriving at Mars eight months later, it uses friction between its aeroshield and Mars's atmosphere to brake itself into orbit around Mars, and then lands with the help of a parachute. This payload is the Earth Return Vehicle (ERV), and it flies out to Mars with its two methane/oxygen-driven rocket propulsion stages unfuelled. It also has with it 6 tonnes of liquid hydrogen cargo, a 100-kilowatt nuclear reactor mounted in the back of a methane/oxygen-driven light truck, a small set of compressors and an automated chemical processing unit, and a few small scientific rovers.

As soon as landing is accomplished, the truck is telerobotically driven a few hundred metres away from the site, and the reactor is deployed to provide power to the compressors and chemical processing unit. The hydrogen brought from Earth can be quickly reacted with the Martian atmosphere, which is 95 per cent carbon dioxide gas (CO_2), to produce methane and water, and this eliminates the need for long-term storage of cryogenic hydrogen on the planet's surface. The methane so produced is liquefied and stored, while the water is electrolysed to produce oxygen, which is stored, and hydrogen, which is recycled through the methanator. Ultimately, these two reactions (methanation and water electrolysis) produce 24 tonnes of methane and 48 tonnes of oxygen. Since this is not enough oxygen to burn the methane

NASA, OPPORTUNITY MARS EXPLORATION ROVER (MER), 2003
Artist's concept. Though a great technical success, in 10 years Opportunity has only travelled a distance that a human explorer could transverse in one day.

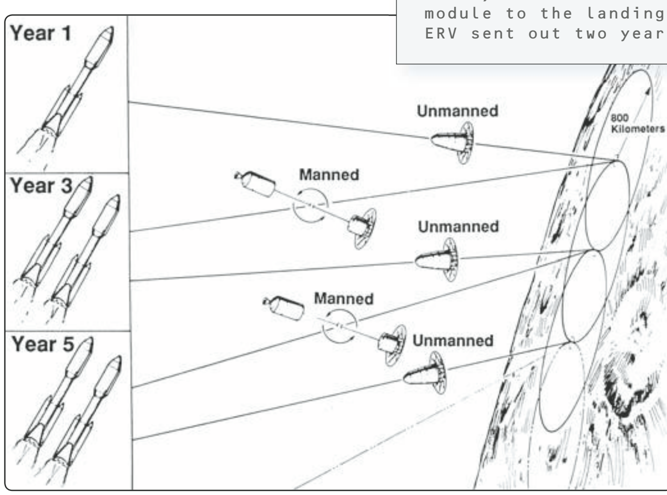
at its optimal mixture ratio, an additional 36 tonnes of oxygen is produced via direct dissociation of Martian CO_2.

The entire process takes 10 months, at the conclusion of which a total of 108 tonnes of methane/oxygen bipropellant will have been generated. This represents a leverage of 18:1 of Martian propellant produced compared to the hydrogen brought from Earth needed to create it. Ninety-six tonnes of the bipropellant will be used to fuel the ERV, while 12 tonnes are available to support the use of high-powered, chemically fuelled long-range ground vehicles. Large additional stockpiles of oxygen can also be produced, both for breathing and for turning into water by combination with hydrogen brought from Earth. Since water is 89 per cent oxygen (by weight), and since the larger part of most foodstuffs is water, this greatly reduces the amount of life-support consumables that need to be hauled from Earth.

The propellant production having been successfully completed, in 2024 two more boosters lift off the Cape and throw their 40-tonne payloads towards Mars. One of the payloads is an unmanned fuel-factory/ERV just like the one launched in 2022; the other is a habitation module containing a crew of four, a mixture of whole food and dehydrated provisions sufficient for three years, and a pressurised methane/oxygen-driven ground rover. On the way out to Mars, artificial gravity can be provided to the crew by extending a tether between the habitat and the burnt-out booster upper stage, and spinning the assembly. Upon arrival, the manned craft drops the tether, aero-brakes, and then lands at the 2022 landing site where a fully fuelled ERV and fully characterised and beaconed landing site await it.

With the help of such navigational aids, the crew should be able to land right on the spot; but if the landing is off course by tens or even hundreds of kilometres, the crew can still achieve the surface rendezvous by driving over in their rover; if they are off by thousands of kilometres, the second ERV provides a backup. However, assuming the landing and rendezvous at site number 1 is achieved as planned, the second ERV will land several hundred kilometres away to start making propellant for the 2026 mission, which in turn will fly out with an additional ERV to open up Mars landing site number 3. Thus every other year, two heavy lift boosters are launched: one to land a crew, and the other to prepare a site for the next mission, for an average launch rate of just one booster per year to pursue a continuing programme of Mars exploration. This is clearly affordable. In effect, this pioneer approach removes the manned Mars mission from the realm of mega-fantasy and reduces it to practice as a task of comparable difficulty to that faced in launching the Apollo missions to the Moon.

ROBERT MURRAY/MARS SOCIETY, MARS DIRECT MISSION BASE, 1998
The hab module is shown on the left, and the Earth Return Vehicle to the right.



ROBERT MURRAY/MARS SOCIETY, MARS DIRECT MISSION SEQUENCE, 1998
Every two years, two boosters are launched to Mars. One sends an unmanned Earth Return Vehicle (ERV), the other sends a crewed hab module to the landing site of the ERV sent out two years earlier.

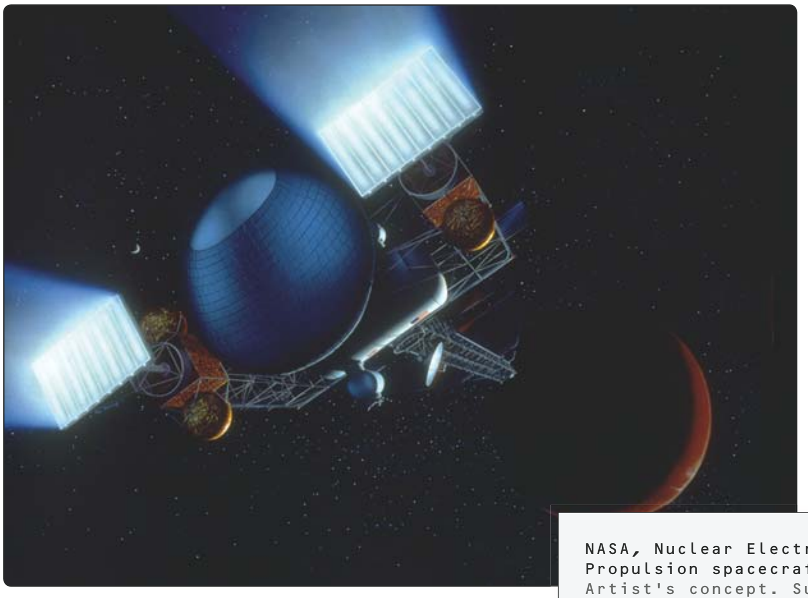
The crew will stay on the surface for one and a half years, taking advantage of the mobility afforded by the high-powered chemically driven ground vehicles to accomplish a great deal of surface exploration. With a 12-tonne surface fuel stockpile, they have the capability for over 24,000 kilometres' (14,900 miles') worth of traverse before they leave, giving them the kind of mobility necessary to conduct a serious search for evidence of past or present life on Mars – an investigation key to revealing whether life is a phenomenon unique to Earth or general throughout the universe. Since no-one has been left in orbit, the entire crew will have available to them the natural gravity and protection against cosmic rays and solar radiation afforded by the Martian environment, and thus there will not be the strong driver for a quick return to Earth that plagues conventional Mars mission plans based upon orbiting mother ships with small landing parties. At the conclusion of their stay, the crew returns to Earth in a direct flight from the Martian surface in the ERV. As the series of missions progresses, a string of small bases is left behind on the Martian surface, opening up broad stretches of territory to human cognisance.

Colonising Mars

Mars is not just a scientific curiosity, it is a resource-rich world with a surface area equal to all the continents of Earth combined.[2] As hostile as it may seem, the only thing standing between Mars and habitability is the need to develop a certain amount of Red Planet knowhow. This can and will be done by those who go there first to explore.

Among extraterrestrial bodies in our solar system, Mars is singular in that it possesses all the raw materials required to support not only life, but also a new branch of human civilisation. This uniqueness is illustrated most clearly if we contrast Mars with the Earth's Moon, the most frequently cited alternative location for extraterrestrial human colonisation.[3]

In contrast to the Moon, Mars is rich in carbon, nitrogen, hydrogen and oxygen, all in biologically readily accessible forms such as carbon dioxide gas, nitrogen gas, and water ice and permafrost. Carbon, nitrogen and hydrogen are only present on the Moon in parts-per-million quantities. Oxygen is abundant on the Moon, but only in tightly bound oxides such as silicon dioxide (SiO_2), ferrous oxide (Fe_2O_3), magnesium oxide (MgO), and alumina oxide (Al_2O_3), which require very high-energy processes to reduce. Current knowledge indicates that if Mars were smooth and all its ice and permafrost melted into liquid water, the entire planet would be covered with an ocean over 100 metres (330 feet) deep. This contrasts strongly with the Moon, which is so dry that if concrete were found there, lunar colonists would mine it to get the water out. Thus, if plants could be



NASA, Nuclear Electric Propulsion spacecraft, 2002
Artist's concept. Such gigantic futuristic concepts are unnecessary to send humans to Mars.

Robert Murray/Mars Society, Building the Base, 2001
As landings continue, multiple hab modules can be connected to create a base.

grown in greenhouses on the Moon (an unlikely proposition, as we have seen), most of their biomass material would have to be imported.[4]

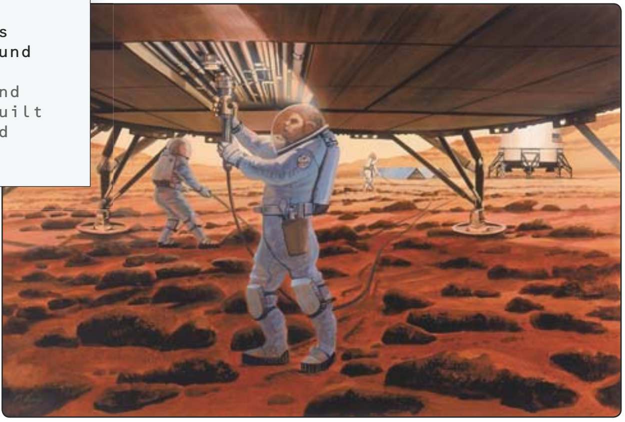
The Moon is also deficient in about half the metals of interest to industrial society (copper, for example), as well as many other elements such as sulphur and phosphorus. Mars has every required element in abundance. Moreover, on Mars, as on Earth, hydrologic and volcanic processes have occurred that are likely to have consolidated various elements into local concentrations of high-grade mineral ore. Indeed, the geologic history of Mars has been compared to that of Africa, with very optimistic inferences as to its mineral wealth implied as a corollary. In contrast, the Moon has had virtually no history of water or volcanic action, with the result that it is basically composed of trash rocks with very little differentiation into ores that represent useful concentrations of anything interesting.

You can generate power on either the Moon or Mars with solar panels, and here the advantages of the Moon's clearer skies and closer proximity to the Sun than Mars roughly balance the disadvantage of large energy storage requirements created by the Moon's 28-day light/dark cycle. But if you wish to manufacture solar panels, so as to create a self-expanding power base, Mars holds an enormous advantage, as only Mars possesses the large supplies of carbon and hydrogen needed to produce the pure silicon required for photovoltaic panels and other electronics. In addition, Mars has the potential for wind-generated power while the Moon clearly does not. But both solar and wind power offer relatively modest potential – tens or at most hundreds of kilowatts here or there. To create a vibrant civilisation, a richer power base is needed, and this Mars has both in the short and medium term in the form of its geothermal power resources, which offer potential for a large number of locally created electricity-generating stations in the 10 MWe (10,000 kilowatt) class. In the long term, Mars will enjoy a power-rich economy based upon exploitation of its large domestic resources of deuterium fuel for fusion reactors. Deuterium is five times more common on Mars than it is on Earth, and tens of thousands of times more common on Mars than on the Moon.

However, the biggest problem with the Moon, as with all other airless planetary bodies and proposed artificial free-space colonies, is that sunlight is not available in a form useful for growing crops. A single acre of plants on Earth requires 4 MW of sunlight power, a square kilometre needs 1,000 MW. The entire world put together does not produce enough electric power to illuminate the farms of the state of Rhode Island, that agricultural giant. Growing crops with electrically generated light is just economically hopeless. But you cannot

Robert Murray/Mars Society, Mechanics on the Red Planet, 2001
top: Servicing equipment at a Mars base.

Robert Murray/Mars Society, Underground Vaults, 2001
bottom: Underground vaults could be built to create expanded habitation space.



use natural sunlight on the Moon or any other airless body in space unless you put walls on the greenhouse thick enough to shield out solar flares, a requirement that enormously increases the expense of creating crop land. Even if you did that, it would not do you any good on the Moon, because plants will not grow in a light/dark cycle lasting 28 days.

On Mars there is an atmosphere thick enough to protect crops grown on the surface from solar flares. Therefore, thin-walled inflatable plastic greenhouses protected by unpressurised UV-resistant hard-plastic shield domes can be used to rapidly create cropland on the surface. Even without the problems of solar flares and a month-long diurnal cycle, such simple greenhouses would be impractical on the Moon because they would create unbearably high temperatures. On Mars, in contrast, the strong greenhouse effect created by such domes would be precisely what is necessary to produce a temperate climate inside. Such domes up to 50 metres (160 feet) in diameter are light enough to be transported from Earth initially, and later on they can be manufactured on Mars out of indigenous materials. Because all the resources to make plastics exist on Mars, networks of such 50- to 100-metre domes could rapidly be manufactured and deployed, opening up large areas of the surface to both shirt-sleeve human habitation and agriculture.

On Mars there is an atmosphere thick enough to protect crops grown on the surface from solar flares. Therefore, thin-walled inflatable plastic greenhouses protected by unpressurised UV-resistant hard-plastic shield domes can be used to rapidly create cropland on the surface.

Robert Murray/Mars Society, Farming on Mars, 2001
Greenhouse agriculture will serve to help make the base self-sufficient.

And that is just the beginning, because it will eventually be possible for humans to substantially thicken Mars's atmosphere by forcing the regolith to outgas its contents through a deliberate programme of artificially induced global warming. Once that has been accomplished, the habitation domes could be virtually any size, as they would not have to sustain a pressure differential between their interior and exterior. In fact, once that has been done, it will be possible to raise specially bred crops outside the domes.

The point to be made is that unlike colonists on any other known extraterrestrial body, Martian colonists will be able to live on the surface, not in tunnels, and move about freely and grow crops in the light of day. Mars is a place where humans can live and multiply to large numbers, supporting themselves with products of every description made out of indigenous materials. Mars is thus a place where an actual civilisation, not just a mining or scientific outpost, can be developed. And significantly for interplanetary commerce supporting operations in the resource-rich asteroid belt, Mars and Earth are the only two locations in the solar system where humans will be able to grow crops for export.

The New World

Mars is the New World. Someday millions of people will live there. What language will they speak? What values and traditions will they cherish, to spread from there as humanity continues to move out into the solar system and beyond? When they look back on our time, will any of our other actions compare in value to what we do today to bring their society into being?

We now have the opportunity to be the founders, the parents and shapers of a new and dynamic branch of the human family, and by so doing put our stamp upon the future. It is a privilege not to be disdained lightly.

Notes

1. Robert Zubrin with Richard Wagner, *The Case for Mars: The Plan to Settle the Red Planet and Why We Must*, Free Press (New York), 2nd edn, 2011.
2. Hugh H Kieffer, Bruce M Jakosky, Conway Snyder and Mildred Shapley Matthews, *Mars*, University of Arizona Press (Tucson and London), 1992.
3. John S Lewis, Mildred S Matthews and Mary L Guerrieri, *Resources of Near Earth Space*, University of Arizona Press (Tucson and London) 1993.
4. Grant Heiken, David Vaniman and Bevan M French, *Lunar Sourcebook*, Cambridge University Press (Cambridge), 1991.

Robert Murray/Mars Society, New Life on a New World, 2001
Over time, the Mars base will grow into a true settlement, the beginning of a new branch of human civilisation.

Neil Leach

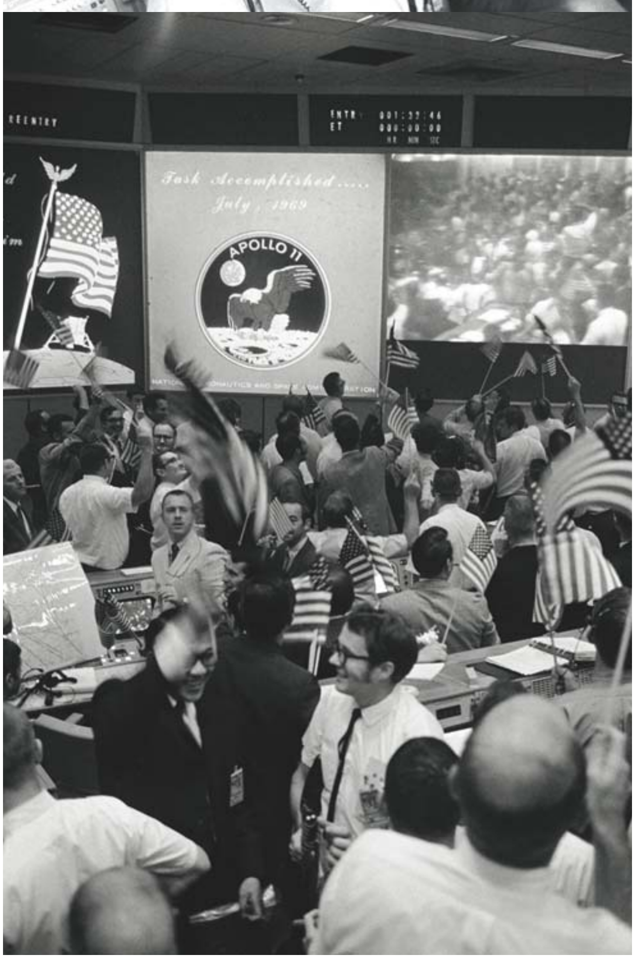
TERESTRIAL SPACE ARCHITECTURE

Space Architecture is not just confined to the extraterrestrial. Guest-Editor **Neil Leach** describes how the burgeoning space tourism industry and cultural buildings dedicated to the legacy of space exploration are potentially leading to more earthbound space structures. Here, Leach profiles Foster + Partners' Spaceport America in the Jornada del Muerto desert, New Mexico, and Bevk-Perovi, Dekleva-Gregori, OFIS arhitekti and SADAR+VUGA's Cultural Centre of European Space Technologies (KSEVT) in Vitanje, Slovenia.

Vehicle Assembly Building, Kennedy Space Center, Cape Canaveral, Florida, 8 September 1969
The Apollo 12 Saturn 5 space vehicle exiting the Vehicle Assembly Building at the start of its journey to the launch pad.

Launch Control Center, Merritt Island, Florida, 16 July 1969
NASA personnel watch as the Saturn V rocket carrying the Apollo 11 astronauts lifts off from the launch pad at Cape Canaveral.

Mission Control, Houston, Texas, 24 July 1969
Flight controllers at NASA's Mission Control Center celebrate the successful conclusion of the Apollo 11 mission.

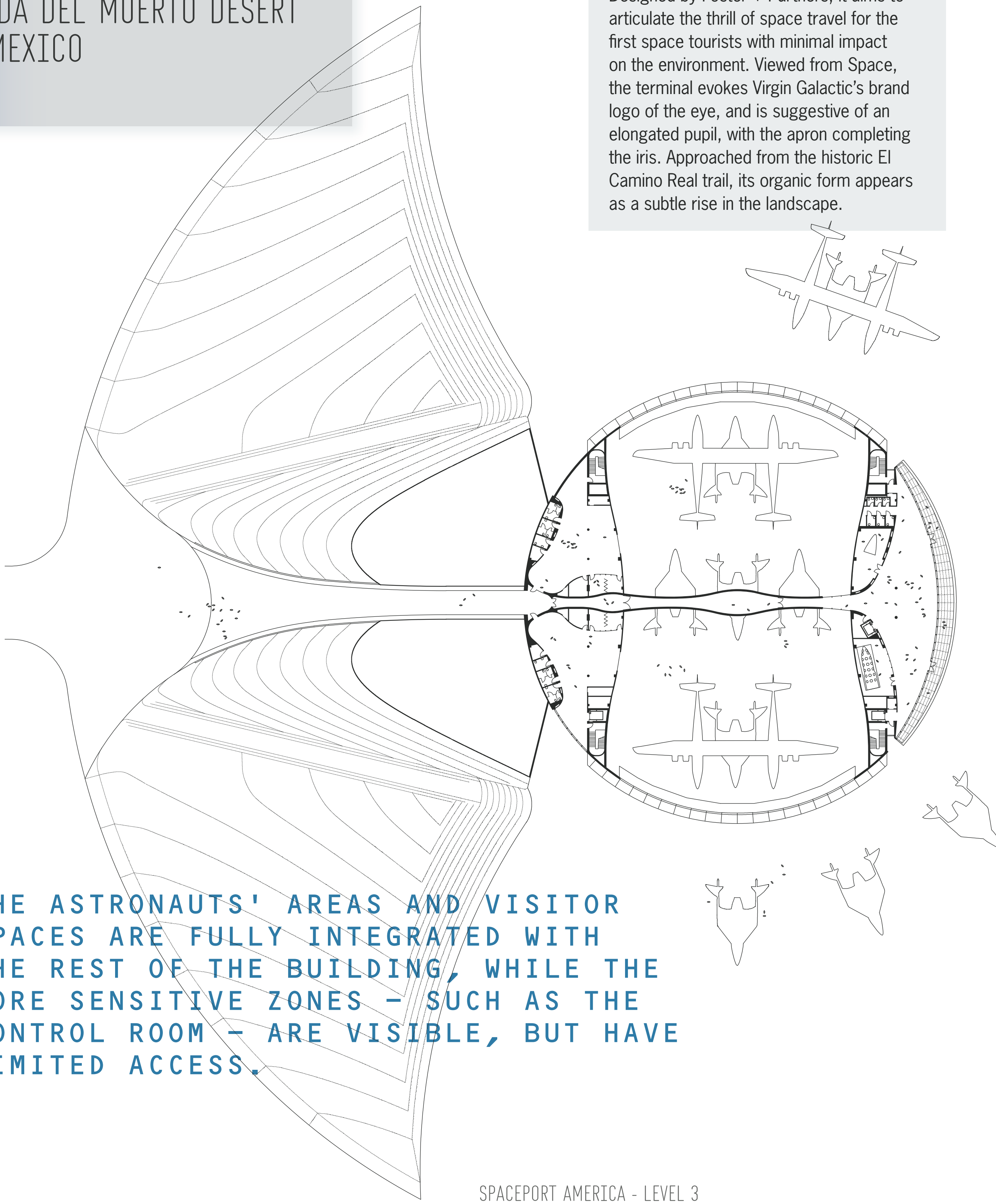


Given that there is only one structure in Space – the International Space Station – that can properly be called a space habitat, the number of examples of terrestrial space buildings far exceeds the number of actual space buildings. Though many are inaccessible to the general public for security reasons, two such buildings – Mission Control in Houston, Texas, and the Launch Control Center and Vehicle Assembly Building in Cape Canaveral, Florida – were nonetheless beamed into the living rooms of every family watching the various NASA missions on TV – especially during the heady days of the Apollo programme (1967–72) – and have become the public face of terrestrial space architecture.

We can detect, however, a new phase of development of terrestrial space architecture. As space tourism draws ever closer, the general public will soon have the opportunity of experiencing not only Space itself, but also, by definition, terrestrial space buildings, such as spaceports, that constitute access points for these experiences. Alongside this, an increasing number of cultural buildings dedicated to the legacy of the space industry are being constructed, including Foster + Partners' Spaceport America in the Jornada del Muerto desert basin in New Mexico (opened 2011) and the Cultural Centre of European Space Technologies (KSEVT) in Vitanje, Slovenia, designed by architects Bevk-Perović, Dekleva-Gregorič, OFIS arhitekti and SADAR+VUGA (opened 2012).

FOSTER + PARTNERS
SPACEPORT AMERICA
JORNADA DEL MUERTO DESERT
NEW MEXICO
2011

Located in the Jornada del Muerto desert basin in New Mexico, Spaceport America is the first building of its kind in the world. Designed by Foster + Partners, it aims to articulate the thrill of space travel for the first space tourists with minimal impact on the environment. Viewed from Space, the terminal evokes Virgin Galactic's brand logo of the eye, and is suggestive of an elongated pupil, with the apron completing the iris. Approached from the historic El Camino Real trail, its organic form appears as a subtle rise in the landscape.



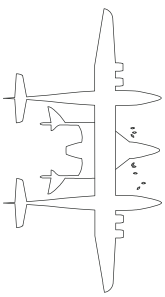
THE ASTRONAUTS' AREAS AND VISITOR SPACES ARE FULLY INTEGRATED WITH THE REST OF THE BUILDING, WHILE THE MORE SENSITIVE ZONES – SUCH AS THE CONTROL ROOM – ARE VISIBLE, BUT HAVE LIMITED ACCESS.

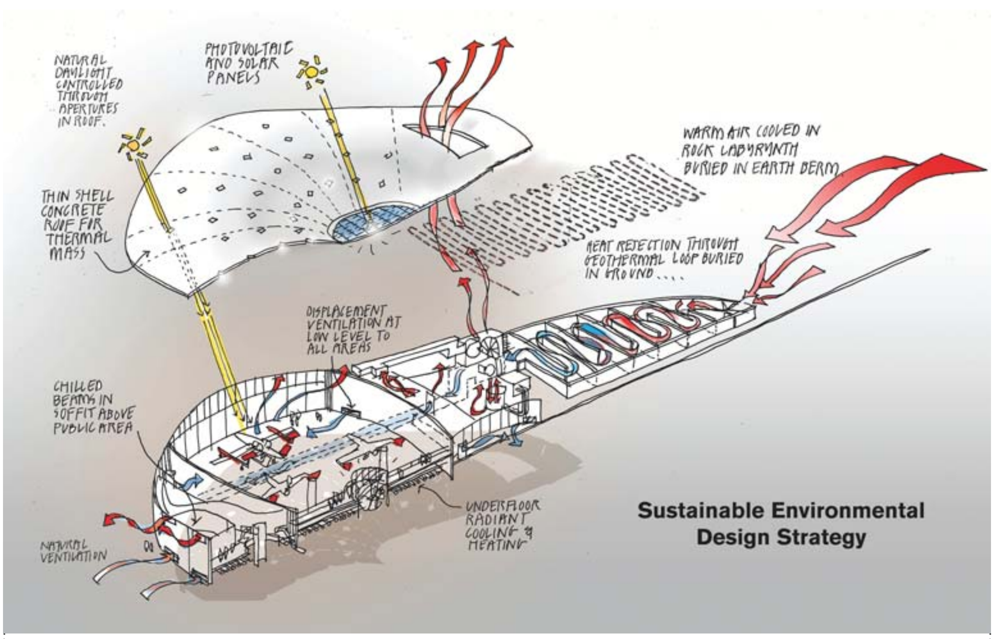
SPACEPORT AMERICA - LEVEL 3

0 5 10

Organised into a highly efficient and rational plan, Spaceport has been designed to relate to the dimensions of the spacecraft. There is also a careful balance between accessibility and privacy. The astronauts' areas and visitor spaces are fully integrated with the rest of the building, while the more sensitive zones – such as the control room – are visible, but have limited access. The building is entered via a deep channel cut into the landscape. The retaining walls form an exhibition space that documents a history of space exploration alongside the story of the region and its settlers. The strong linear axis of the channel continues into the building on a galleried level to the super hangar – which houses the spacecraft and the simulation room – through to the terminal building. A glazed facade overlooking the runway establishes a platform within the terminal building for coveted views out to arriving and departing spacecraft.

With minimal embodied carbon and few additional energy requirements, the scheme was awarded the prestigious LEED Gold accreditation in 2014. The low-lying form is recessed into the landscape to exploit the thermal mass, which buffers the building from the extremes of the New Mexico climate as well as catching the westerly winds for ventilation, and maximum use is made of daylight via skylights. Built using local materials and regional construction techniques, Spaceport aims to be both sustainable and sensitive to its surroundings.



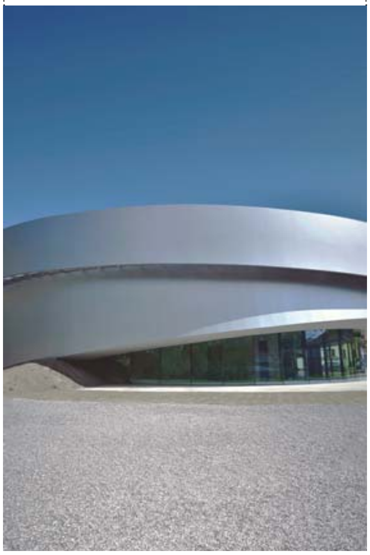


Sustainable Environmental Design Strategy

BUILT USING LOCAL MATERIALS AND REGIONAL CONSTRUCTION TECHNIQUES, SPACEPORT AIMS TO BE BOTH SUSTAINABLE AND SENSITIVE TO ITS SURROUNDINGS.

BEVK-PEROVIĆ, DEKLEVA-GREGORIČ, OFIS ARHITEKTI AND SADAR+VUGA,
CULTURAL CENTRE OF EUROPEAN SPACE TECHNOLOGIES (KSEVT), VITANJE, SLOVENIA
2012

The Cultural Centre of European Space Technologies (KSEVT) is situated in Vitanje, Slovenia, the hometown of Herman Potočnik (pseudonym Hermann Noordung) (1892–1929), an early rocket scientist and pioneer of cosmonautics. It is designed to house social, cultural and scientific activities, conferences and club/study activities, as well as permanent and temporary exhibitions. The design of the building derives from the habitable wheel of the first geostationary space station described in Noordung's book *The Problem of Space Travel: The Rocket Motor*, originally published in 1929. Noordung's space station was designed as a geostationary satellite composed of three elements: a solar power station, observatory and habitable wheel. Although never realised, his design remains one of the most revolutionary proposals for a space station. The rotating habitable wheel, a circular construction setting up artificial gravity through centrifugal forces, is one of the simplest solutions for the problem of weightlessness in long-term human habitation. A station in this orbit could also represent a perfect point of departure for longer space flights, considering that the Earth's gravitational force is still one of the greatest obstacles. Indeed one such station appears in Stanley Kubrick's film *2001: A Space Odyssey* (1968).



What makes the design of the Cultural Centre of European Space Technologies distinctive is that it is a collaboration between four architectural offices. The client initially invited four offices to compete for the design in a limited competition, but the office principals decided to do the project together. The building is a monolithic concrete structure, positioned between a main road on one side and a stream with a green hinterland on the other. The exterior and interior of the building are made of two low cylinders. The bottom one is larger and rises from the north to the south, while the upper cylinder is smaller and joins the larger one on the south while rising to the north. The bottom cylinder is supported by the transparent surface of the entrance glazing. From the exterior, there is a dynamic play between the two cylinders, accentuated by the continuous glass ring that surrounds the building. The building appears to float and rotate on its southern and western sides towards the road, and is recessed into the ground on the other side, giving it a connection to its immediate surroundings. The spatial effect of floatation and rotation give it the feeling of artificial gravity.

FROM THE EXTERIOR, THERE IS A DYNAMIC PLAY BETWEEN THE TWO CYLINDERS, ACCENTUATED BY THE CONTINUOUS GLASS RING THAT SURROUNDS THE BUILDING.

There are two entrances: a main entrance into the central space from the square in front of the building, and a secondary one to the rear. The main entrance is below the overhanging part of the bottom cylinder. The vestibule can be separated from the activities in the hall by a curtain. Alternatively, the entrance glazing can be opened completely, connecting the activities in the hall with the square. The circular hall, for 300 people, is surrounded on both sides by a semicircular ramp marking the beginning of the exhibition area and continuing right up to the overhanging part of the larger cylinder.

Along the ramp there are smaller offices. Ascending the ramp also represents a transition from the bright space of the hall to the dark exhibition area. A staircase and large elevator connect the exhibition area directly to the vestibule of the hall. The exhibition space continues through the landing between the elevator and the staircase to the smaller cylinder, the multipurpose hall, and a raised auditorium above from which one can observe the activities below. At the top of the smaller cylinder is a club area devoted to researchers of the history of space technology.

The Future of Terrestrial Space Architecture

Terrestrial space architecture is necessarily tied to space exploration itself. As the number of countries becoming involved in the space industry increases, so we can expect an increase in the construction of terrestrial space-related buildings. Russia already has considerable such facilities in support of its own longstanding space programme, and with China also building up its own space programme and planning to send the Tiangong space station into low earth orbit by around 2020, alongside other countries, such as India, with similar ambitions, in the future we can expect to see many new examples not only of space habitats, but also of terrestrial space architecture.

In reality, however, most actual space habitats – aside from fantasy-based design fictions such as the New City installation by Greg Lynn (see pp 82–9 of this issue) – are restricted by exacting constraints and characterised by efficient, performance-based logics of design. Perhaps, then, it will always be left to terrestrial space buildings, such as the Cultural Centre of European Space Technologies, to convey that exuberance and excitement of space travel itself. ⌂

THE CIRCULAR HALL, FOR 300 PEOPLE, IS SURROUNDED ON BOTH SIDES BY A SEMICIRCULAR RAMP MARKING THE BEGINNING OF THE EXHIBITION AREA AND CONTINUING RIGHT UP TO THE OVERHANGING PART OF THE LARGER CYLINDER.

WAITING FOR IGNITION

Space tourism is in its infancy, having been launched a little over a decade ago by billionaire businessman Dennis Tito's venture into Space. **Ondřej Doule**, Assistant Professor of Human-Centered Design and Aerospace Engineering at the Florida Institute of Technology, and Chair of the Space Architecture Technical Committee at the AIAA, considers the shift that will have to be made in designing Space Architecture as space shuttles and stations transition from being ostensibly high-security labs into floating hotels.

Ondřej Doule

SPACE TOURISM

Virgin Galactic, SpaceShipTwo during its second powered flight, September 2013
SpaceShipTwo will carry six space tourists and two pilots to the edge of Space where they will enjoy a few minutes of microgravity and views of Earth and Space. SpaceShipTwo is an evolved version of SpaceshipOne, the first commercial spaceship to reach Space in 2004.

While travelling for pleasure across the Earth is an established and ancient pursuit, travel into Space is still in the most formative of stages, with the first paying passenger, Californian billionaire businessman Dennis Tito, only going into space in 2001, on board the Russian Soyuz TM spaceship. Even though extremely confined and uncomfortable, Soyuz can be considered safe and reliable as it includes emergency escape features and has the capability to recover and protect crew in almost any phase of the flight. However, it will not be sufficient for space tourism of the near future and the needs of the general public. Its non-reusable design and low capacity mean it is unsuitable for frequent travels to Space and back.

Safety First

All space activities are linked to national security and safety. Over the last 40 years, national pride and security have been the main drivers of human travel to Space, followed by research and science that has prevailed in the past 20 years, culminating in the International Space Station. Global political stabilisation and economic, societal and technological growth provide a solid basis for the establishment of commercial space travel in the 21st century. National security is still the primary reason for investment in Space, Earth observations and space exploration. However, entrepreneurial commercial interest and private investment will stimulate research on human space travel as well as the search for new energy and mineral resources.

Space tourism ultimately relies on the capacity and safety of the means of transport. The extreme environmental conditions encountered in Space, and travelling many times faster than in a commercial airliner, make human control of the system much more difficult. A high level of automation is therefore required to ensure precise vehicle control, leaving space transportation highly dependent on systems directly supervised from the terrestrial ground station.

Suborbital Tourism

Since the Space Shuttle program ended in 2011, there are only two spaceships left that are capable of carrying humans to Space: the Russian Soyuz TMA that is subcontracted by NASA, and the Chinese Shenzhou that is based on the Soyuz platform and currently used only for Chinese 'taikonauts'. While space tourism (or private space exploration) began with Tito's self-funded trip 13 years ago, private companies are only just starting to offer trips to Space in commercial spaceships. A number of companies are working on commercial access to Space, developing their own spaceships, rocket planes, rockets, re-entry modules and orbital hotels. Virgin Galactic is a leader in so-called 'suborbital tourism', and no one doubts that suborbital transcontinental flights (cutting down transport times by many hours) are on its agenda.

The currently offered suborbital flight is a trip to Space that lasts a few hours with a peak of a few minutes of microgravity. These trips are estimated to be operational in 2015, and many tickets have been already sold. The unofficial threshold of Space, 100 kilometres (60 miles) above the Earth's sea level, is the point that should be acceded during this flight, and where tourists will experience weightlessness and stunning views of the Earth and Space.

The launch will also be an unforgettable experience for the 'space flight participants' (as the Federal Aviation Administration defines space tourists), during which they will 'enjoy' rapid acceleration from the rocket engine – at peaks of over 6Gxz (6Gx) – and, one could say, a less 'comfortable ride' than the astronauts who flew the Space Shuttle (only 3.5Gx acceleration). Tourists will have to undergo short training and basic medical screening before the flight.

The Virgin Galactic spaceship is carried by a WhiteKnight plane that drops the spaceship and its six space tourists (paying $250,000 per ticket), pilot and co-pilot at high altitude, around 16 kilometres (10 miles) from Earth, and lets the spaceship glider ignite its only propulsion system. After a steep ascent, the cabin of the spaceship reconfigures (seats will fold down) to enable comfortable floating around in microgravity. Tourists will be trained to get back on their seats for safety reasons before atmospheric re-entry, and the rocket plane will glide back to the Spaceport America in the Jornada del Muerto desert basin in New Mexico (see pp 56–9).

SpaceX, Dragon 2 spaceship, May 2014
opposite top: The SpaceX Dragon 2 spaceship interior for seven astronauts significantly exceeds the capacity of current space vehicles. Its flight profile is similar to Apollo or Soyuz spacecraft, utilising a blunt body configuration for deceleration in Earth's atmosphere. Astronauts are seated with their backs parallel to the heat shield to mitigate possible G-load in a safe chest-to-back direction.

opposite bottom: Dragon 2 is a reusable vertical take-off, vertical landing (VTVL) vehicle with high-precision landing capability. It uses parachutes followed by the propulsive landing system (rocket engines) to control the deceleration as well as steering. In case of a failure, the spaceship can safely land with only two rocket engines operational.

Virgin Galactic, SpaceShipTwo, 2006
below: Space flight participants will be in a comfortable interior, sitting in reclining seats that will help to mitigate the acceleration from the rocket engine during ascent and re-entry.

XCOR Aerospace represents a different approach to the suborbital experience. Its Lynx spaceship is a smaller, one-stage vehicle for one passenger and one pilot, that takes off from a runway using its rocket engines and lands as a glider. This vehicle is designed for high turnaround, capable of several flights to Space per day. XCOR has already established partnerships with airline providers in a bid to target the 'mass market' by selling tickets for no more than $90,000.

The American aerospace industry is booming with commercial human space flight, not only to suborbital destinations, but also to low earth orbit. In fact, the first commercial Space Exploration Technologies Corporation (SpaceX) (for now unmanned) spaceships have already docked on the International Space Station and are now being prepared for human space flight. SpaceX is shooting high. Its Dragon spaceship is being prepared for human space flight and will provide transport capability to low earth orbit and beyond very soon. Its recently unveiled Dragon 2 is a high-capacity reusable spaceship that could be adopted for trips to Mars.

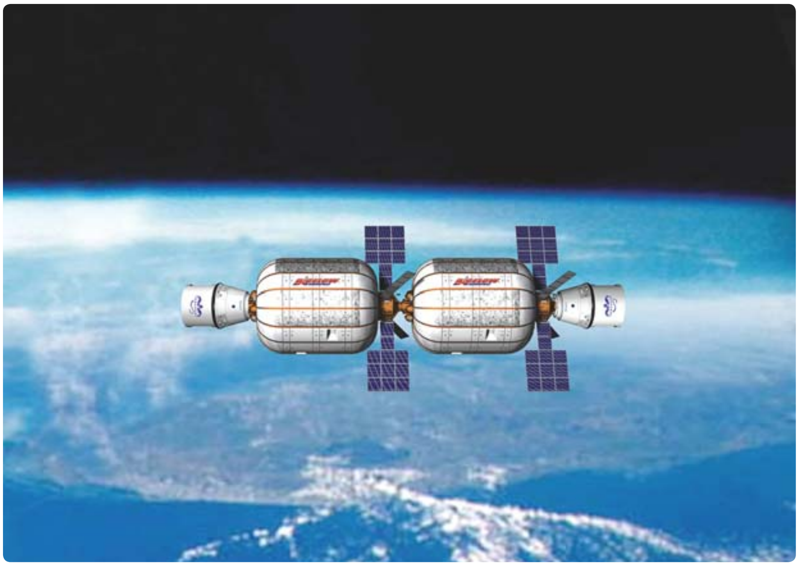
In addition to commercial spaceships, commercial spaceports for space tourism flights that also support tourist training are being built or adapted from airline airports around the world (for example, Spaceport America, Space Experience Curacao, Spaceport Sweden and Spaceport Malaysia).

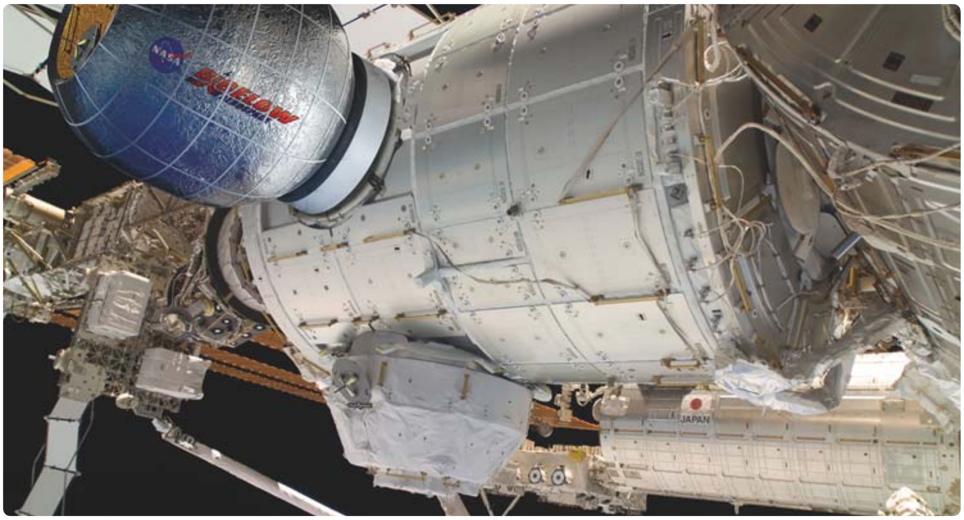
The American aerospace industry is booming with commercial human space flight, not only to suborbital destinations, but also to low earth orbit.

Bigelow Aerospace, BA330 space hotel modules, 2014
top: Two inflatable orbital habitat modules with docked SpaceX Dragon spaceships. Each module has a habitable volume of 330 cubic metres (11,650 cubic feet), which means it could accommodate up to 12 people for missions shorter than 180 days, according to current NASA standards.

Bigelow Aerospace, Bigelow Expandable Activity Module (BEAM), 2014
bottom: The BEAM inflatable module is a smaller version of the BA330, and is due to arrive at the International Space Station in 2015 onboard the SpaceX Dragon spaceship. It will provide an extended habitable environment for the space station crew and will be the first inflatable habitable module in space.

It is estimated that mass space tourism will begin with short suborbital flights in a few years, and that space tourists will require completely different cabin interiors to those of current spaceships.





The Challenge for Designers

It is estimated that mass space tourism will begin with short suborbital flights in a few years, and that space tourists will require completely different cabin interiors to those of current spaceships. The training of the space flight participants will be significantly shorter, and thus human–system integration and interfaces will need to be more intuitive, simple and reliable. Interiors will also need to be more attractive – something national agencies have paid little attention to. Unpredictable human behaviour and the variety of risk scenarios will need to be incorporated in the system design and its risk mitigation strategies. Automatic adaptive cabin features such as technological prostheses may need to be used in the interior to support human functions and needs in the microgravity and hypergravity parts of the flight.

Mastering the human–system integration and supporting human adaptation to the unfamiliar environment is an important task. Passengers will likely feel discomfort when, for example, hanging upside down in microgravity; just as the heart pumps blood vigorously to get it circulating around the whole body against gravity in normal terrestrial conditions, it will have to decrease its rate in microgravity conditions, and passengers will have to adjust to the feeling of higher blood pressure. Another necessity is learning how to coordinate motion and orient in microgravity, or how to spatially support it by design. Soft wall surfaces will be an important safety and design feature, as well as spatial navigation clues using either high-contrast colour or geometry, as the cabin designs will not have ceilings or floors.

Ondřej Doule/Space Innovations, Omicron v2 space hotel, low earth orbit, 2014
above: The interior has an innovative flexible wall system for maximum safety in microgravity.

below: The concept of the Omicron v2 space hotel is based on off-the-shelf components and integrated in an existing Salyut/Zvezda frame. It can accommodate two to three space tourists for stays of up to 12 days.

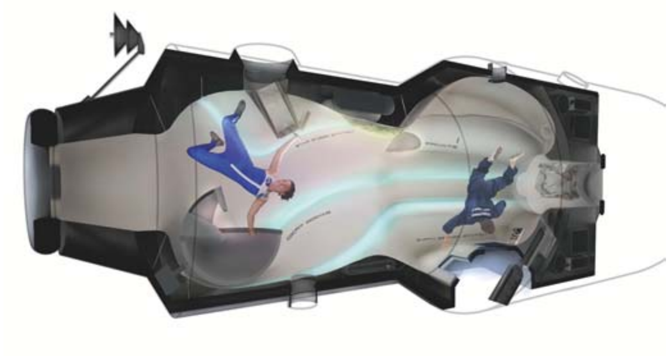
Space Vacation

As commercial transportation to Space becomes more available, commercial space facilities such as space hotels will be needed. Bigelow Aerospace is the first to develop a very effective inflatable structure (Sundancer, with a further, large BA330 module) intended for use as a space hotel. The BA330 is a habitable component with a capacity of 330 cubic metres that can be modularly clustered. Its inflatable habitat technology is based on the NASA TransHab concept that was supposed to be part of the International Space Station but was never implemented. Bigelow has already tested two prototypes in low earth orbit (the Genesis I and II modules) and signed a contract with NASA to connect its BEAM habitability module to the International Space Station in the near future.

Thus the architects have another challenge ahead of them: to get familiar with deployable, inflatable and hybrid structures and systems that are much more efficient (regarding internal volume capacity) than purely rigid structures and have the construction process integrated within the structure.

Earth and Space observations and motion in microgravity may be the main interests now, but it is the space tourists who will define their activities through experimentation, creativity and needs: a microgravity shower or spa, a microgravity bar with a dance 'floor', a space honeymoon?

The possibility of making a round trip to any place on Earth in one day is certainly very interesting, not only for executives and businessmen, but also for cargo and rescue purposes. Thus conventional aviation may become the second most used mean of transportation in the future, behind suborbital flight, in the same way that passenger boats did after the evolution of passenger aeroplanes. The challenge, though, lies not only in enabling space tourism, but also in coordinating it with current high-density aviation air traffic. ⌂



A L P H A

Alpha in operation: the International Space Station as seen from Atlantis STS-135, July 2011
The International Space Station in operation, as seen from Atlantis having completed its delivery of research and logistics cargo and starting its return to Earth.

Constance Adams and Rod Jones

FROM THE INTERNATIONAL STYLE TO THE INTERNATIONAL SPACE STATION

How has a Modernist predilection for the modular contributed to the design of Space Architecture? Leading space architects **Constance Adams and Rod Jones** highlight how by embracing a diligent modularity in the early 1980s, NASA initiated a design approach that has enabled replicability, flexibility and technological transparency, and has proved the International Space Station resilient in the face of multiple logistical, financial and political challenges.

Modularity: What could be more modern? In the decade and a half of engineering studies beginning in the early 1980s that resulted in the design of today's International Space Station, NASA for the first time enunciated the importance of modularity as a fundamental Modernist design principle that would enable completion of the station (also known as 'Alpha') despite political and technological upheaval. In a 1984 document entitled 'Space Station Reference Configuration', NASA set forth four of the most fundamental ideologies of 20th-century architecture: replicability, trans-cultural relevance, flexibility and technological transparency:

> Inherent in the program objectives is that the manned Space Station have the capability to grow in its ability to provide basic services to all types of customers, and to accommodate additional users of foreseen and unforeseen classes …
> The requirement that the Space Station become a permanent facility implies that, in addition to growth capability, it must also possess the characteristic of being able to incorporate advances in technology as they occur. This compatibility with 'modernization', or technology transparency, is then considered a significant design driver.[1]

Only three years into the Space Shuttle's service life, this document – which kicked off the second major wave of design studies for what would become the International Space Station – formed the groundwork for the next five years of design planning. As the history of the design and construction of that orbital platform demonstrates, modularity is an extremely powerful architectural approach for applications or projects with large unknown or uncertain components. Whether logistical, financial, temporal, political or technological, the challenges that can prove fatal for a major project can be overcome by a diligently modular design.

Modernism and Modularity

From the Congrès Internationaux d'Architecture Moderne's (CIAM's) first Modernist manifesto of 1928, the ideals of the International Style focused on the rationalised standardisation of building structures into modules that allowed for efficient, economical production, transportation and deployment in almost any environment. This idea was not only modern, but self-consciously international, in that the formation of industrially produced standard living modules would supersede physical and political boundaries and override cultural chauvinism with the ineluctable calculus of efficiency and efficacy.[2] That the signatories of the CIAM manifesto, written at the Swiss villa of La Sarraz, would go on to build housing and cultural facilities throughout a Europe devastated by the First World War, in the Soviet Union and across North and South America, speaks volumes to the truth behind the organisation's assertion of internationalism.

An offshoot of the industrial mode of production, the modular design paradigm derived from and fed the Arts and Crafts movement, the Bauhaus, the Garden City movement and Bolshevism – to name only a few of CIAM's ideological fellow travellers of the period.

The economical production methods that formed part of CIAM's argument for modularity involved several major components also important to the ability to build and operate the International Space Station, including: universality of tools for manufacture; compatibility of modular components with

Endeavour, View of the International Space Station from above, March 2010
The Russian segment of the International Space Station is visible below the lateral truss, with the common modules of the US Operating Segment at the centre and top of the image.

prevailing logistical (and launch) platforms; flexibility of form permitting multiple layouts from the same set of building blocks; universality of integration for modern utilities; and, finally, a readiness for acceptance of change – an essential 'modernity'. After two decades of researching options for orbital space platforms, in its 1984 configuration reference document and subsequent configuration control points in 1989, 1993 etc, NASA had condensed the results of dozens of trade studies into structural, technical, operational, logistical, economic, scientific, functional and commercial issues related to the handful of basic design options available to contemporary rocket science. The result was based on all these concerns, condensed into a key handful: logistical compatibility with the Space Shuttle system; commercial availability of manufacturing capability to produce modules; flexibility to resize, reconfigure and/or reorient the Station's primary components; ability to accommodate commercial activity; and ease of maintenance and forward technological compatibility for longevity and robustness.

Most importantly, the International Space Station's history demonstrates definitively the great strengths of modular architecture. Its modularity permitted Alpha to weather major technological, political and logistical crises as well as dozens of smaller economic, cultural and technical challenges along the quarter century from its conceptual design to assembly completion.

NASA's best thinkers and planners came to the conclusion that a diligently modular approach to design and execution would be the best guarantee of success for America's Space Station. As the Modernists had, the steely-eyed missile men concluded that this central design principle was fundamental to the achievement of the orbital platform they had been seeking so long to build. The International Space Station we have today is in many ways the ultimate artefact – the embodiment, the fulfilment – of Modernist architecture. Since before the Mercury missions (1961) launched American astronauts into the Space Age, German rocket engineer Wernher von Braun and his associates had been calculating designs for orbital platforms that would serve as off-planet bases for further missions to the Moon, Mars and beyond.

What the Gemini (1962–6) and Apollo (1967–72) missions had begun to clarify for space flight planners – and what the first US orbital space station Skylab (1973–9) confirmed – was that performing any activities in Space, and particular extra-vehicular activity (EVA), was complex, time-consuming, expensive and potentially risky to such an extent that it was not smart to design a system around Space-based construction. Any components that could be preintegrated on the ground should be delivered to Space as complete as possible, with in-situ activities kept to a minimum of effecting connections and basic integration.[3]

Originally conceptualised as a system capable of an eventual 100 launches per year from two or more spaceports, the Space Transportation System (STS, or Space Shuttle) orbiter was therefore designed (1968–80) with a payload bay sized to carry the largest components that could be transported across North America on the federal rail and highway system. Thus, with the transition to a Shuttle-only based delivery platform, the first step in rationalisation and standardisation of the Space Station had already been taken. Even before the STS was a proven and viable launch system, the logistics of spacecraft component delivery, testing and integration was relatively pedestrian and almost universally reproducible by any party who wanted to join in the venture. By the mid-1980s, when the Space Station configuration was based on common modules sized for the Shuttle, and by the late 1980s when the first international partners signed on to join in the development of the programme, decisions had already been made to cement the first two fundamental Modernist design values into the Station paradigm.

Modularity in Alpha's design language is manifested in four principal systems: the basic modular pressure vessel that forms each of the habitable components, known as the Space Station Common Module; the Rack system that supports all major equipment and functionality within those modules; the Cargo Transfer Bag (CTB), a sub-rack sized set of units for transfer and storage of cargo, payloads and consumables; and the plug-and-play philosophy governing connections and accessibility.

International Space Station, Node 3 module being delivered from Endeavour's payload bay, February 2010
top: Modularity of International Space Station construction: the Russian Soyuz capsule is shown in the foreground, docked to the Russian Segment. An International Space Station robotic arm manoeuvres the Node 3 module from the payload bay onto the US Operating Segment. The Japanese Experiment Module (JEM), known as the Kibo laboratory, and external facility can be seen in the background.

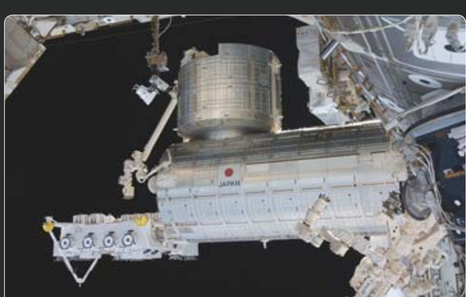
STS-135 crew members inspect the Raffaello mini-pressurised logistics module (MPLM) at the Space Station Processing Facility, NASA Kennedy Space Center, Florida, April 2011
bottom: The four-square utility standoff configuration, with crew standing in open rack bays. International Standard Payload Racks (ISPRs) are installed in the nadir bay above.

Spacelab module, STS-94 Microgravity Science Laboratory mission, 1997
top: Crew operating in the Spacelab module during the 16-day mission.

International Space Station, Japanese Experiment Module Kibo laboratory and Exposed Facility, July 2009
bottom: US Operating Segment common module architecture: the Japanese Experiment Module (JEM) and payload fairing both have rack bays in their external structure.

Space Station Common Module

A key early decision was the choice to abandon unique or monolithic forms for the Space Station architecture and to focus on a facility whose on-orbit assembly could be completed in minimal time and with minimal complexity. Consisting of a crew quarters, laboratory and solar observation station built into what would have been the third stage of the Saturn V rocket originally built to deliver Apollo 18 to the surface of the Moon, Skylab had many features of the early Station studies, including a large-diameter single unit with connected, compatible Service Module and Command Module components. However, some unique elements, including the antennas, telescope and mounts for the Solar Observatory on Skylab's exterior required some installation by astronauts performing EVA manoeuvres, as did repair of the radiation barrier on the Orbital Workshop that had been damaged during launch. These EVA construction activities proved far more complex and time-consuming than anticipated, leading to a reassessment by Space Station planners of the value of on-orbit construction.[4]



Skylab clarified the comparative cost and difficulty of staging an EVA construction crew over several years of activity, with the result that serious mention of complex orbital platforms such as the large, slow rotating wheels strongly favoured by Von Braun's team largely disappeared from NASA planning papers and documents.

By 1984 the Common Module was set at the 14.5-foot (4.4-metre) diameter, 23- to 40-foot (7- to 12-metre) length that the logistical platform would allow. From this point forward, the biggest design questions revolved around what basic architecture to use in outfitting these modules with the utilities, secondary structures, equipment and outfitting they would need to achieve full functionality. Design trade studies – the iterative design tradeoff and selection method common in advanced engineering[5] – eventually resulted in the choice of a four-square configuration, with a central corridor 84 inches square in cross section along the central axis of each module. Equipment would be equally distributed about that open area on all four sides, and a rack system developed to allow flexible equipment accommodation for systems components, cargo and payloads while still permitting rapid access to all parts of the utility runs and pressure shell for maintenance and troubleshooting activities.

Rack System

Design for the equipment carriers hinged around two primary considerations: the ability to accommodate commercial off-the-shelf (COTS) items in a compatible, secure way; and the ability to host large systems items and outfitting such as a sleep station, wardroom, galley or work bench. Since the industry standard equipment rack for audiovisual and computer electronics is a 19-inch (48-centimetre) wide frame, addition of structure to each side generated a 21-inch (53-centimetre) gross width. If doubled, the 19 to 21 inches becomes 38 to 42 inches (96 to 107 centimetres), leaving sufficient clear volume to accommodate a human body performing a number of tasks.

This 'double' 42-inch wide rack, able to swing out from its lower pins and translate through any Common Module or hatch, became the International Space Station baseline,[6] and once this determination was made, a significant part of the complexity in design and assembly was resolved. Where the modularity of the Common Module made transportation and overall facility architecture choices clear, the modularity of the internal racks had enabled a 15-member international programme, comprising tens of thousands of support personnel around the world.

Cargo Transfer Bag (CTB)

A set of lockers was installed in the Space Shuttle orbiter mid-deck to hold cargo during launch and on-orbit operations. To hold the cargo components together, flight integration engineers made up a set of bags sewn from robust ceramid-fibre materials that were sized precisely to fit the inner dimensions of the lockers, and the Shuttle packing systems coalesced around this unit.[7] Because the bags were also useful prior to launch, for transfer of cargo from one centre to another, they were given the designation Cargo Transfer Bag (CTB).

Today, all new cargo carriers for the International Space Station are designed to support packages of the CTB modular system.

Plug-and-Play

Perhaps the most important aspect of any modular architecture, beyond the modules themselves, is the framework holding the modules together. This framework is concrete, metabolic and philosophical. The Space Station philosophy of total maintainability, which drove the design of the trusses, externally accessible resupply elements and payloads, and overall plug-and-play capability, is expressed in the attachment mechanisms and design for EVA accessibility throughout the facility's exterior. Plug-and-play is also visible in systems design, and in Alpha's embrace of forward compatibility with evolving technologies.

The completely maintainable, modular, preintegrated design paradigm also offers much greater potential for longevity due to the plug-and-play functionality of system technologies and subcomponents. The modular, plug-and-play design approach permits frequent replacement as needed, enables the programme to upgrade these systems and thereby to take advantage of new technological developments that would not have been foreseeable when International Space Station assembly began in 2000, and is also projected to support forward compatibility with future models as appropriate.

Atlantis STS-135, the final landing of NASA's Space Shuttle programme, Kennedy Space Center, 21 July 2011
below: On the 37th shuttle mission to the International Space Station, STS-135 delivered the Raffaello multi-purpose logistics module filled with more than 9,400 pounds of spare parts, equipment and supplies to sustain station operations for the next year. STS-135 was the 33rd and final flight for Atlantis and the final mission of the Space Shuttle programme.

Leonardo mini-pressurised logistics module (MPLM), Racks and cargo attached to the International Space Station, November 2008
bottom left: MPLM is the basic standardised cargo container used to transport all types of pressurised cargo, including crew supplies, science, logistics and maintenance hardware, to and from the International Space Station by the Shuttle.

HTV-3 Japanese pressurised cargo vehicle upon arrival at the International Space Station, 2012
bottom right: The modularity of cargo and logistics is clearly visible in the fully-packed Japanese HTV cargo vessel used to resupply the Japanese Experiment Module and International Space Station.

Space Shuttle middeck locker (MDL)
below: An STS-135 NASA astronaut on the middeck of the space shuttle Atlantis accessing tools from a middeck locker.

bottom: Typical example of a Space Shuttle MDL, the standard modular container for storing all mission cargo.

Setbacks

Thanks to the four levels of modularity in design outlined above, the International Space Station was able to overcome multiple challenges, including three main inflection points in technology, geopolitics and logistical support.

Fortunately, all components of today's Station as built are maintainable in Space and can be replaced as needed. However, early design studies identified potential drawbacks to this philosophy: firstly, a marginally higher cost and mass to maintain redundant options for future uses; secondly, the Station's systems would need to support EVA or other on-orbit activities as required to perform repairs; thirdly, in detailed areas there would be a potential loss of equipment-level robustness; and fourthly, an inevitable increase in complexity.

The choice of modularity over custom system architecture for the Space Station sets an important example for future space flight endeavours, particularly those projected to require multiple launches for assembly, logistics and support.

Internationalism at 9 Kilometres per Second

The choice of modularity over custom system architecture for the Space Station sets an important example for future space flight endeavours, particularly those projected to require multiple launches for assembly, logistics and support. Despite a dramatically changed international and political environment, two catastrophic failures and the cancellation of the International Space Station's primary launch platform, Alpha assembly was completed in 2011. Originally a US design, the Station is now the product of more than half a dozen discrete engineering cultures, its primary pressurised modules were built and equipped by four different space agencies, and it continues to support science payloads and enjoy logistical support from up to 15 member nations. As we continue to operate and upgrade the International Space Station, the importance of this lesson becomes increasingly clear, and plays a significant role in the day-to-day planning, maintenance and forecasting of Alpha's future.

Notes
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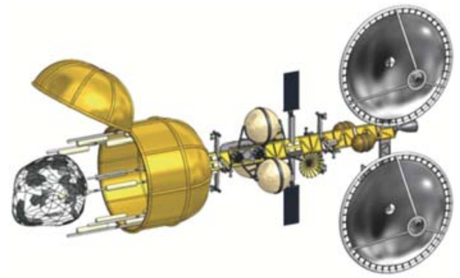
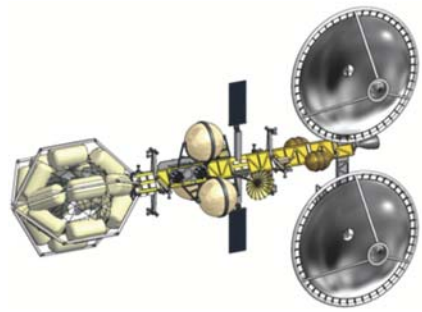
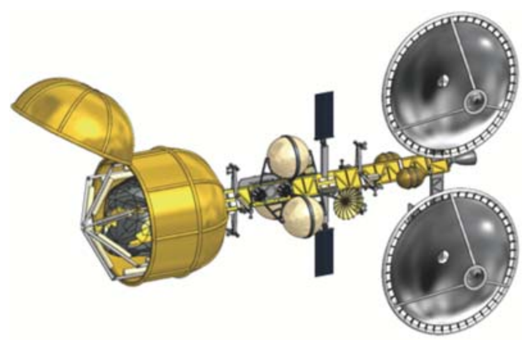
Marc M Cohen



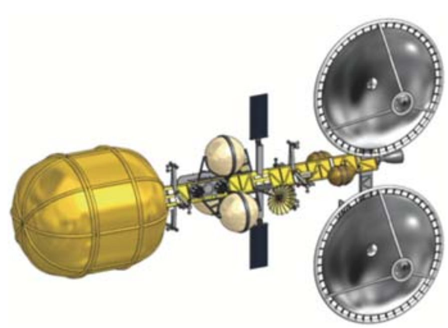
BEING A SPACE ARCHITECT



A space architect for NASA for over 25 years and now the founding principal of Astrotecture™, **Marc M Cohen** highlights how Space Architecture as a discipline differentiates itself from architecture, its terrestrial cousin, by designing structures for the most extreme of environmental conditions. He discusses three design projects undertaken by Astrotecture™ and funded by NASA that emphasise the level of physical problem-solving involved in astronautical design.



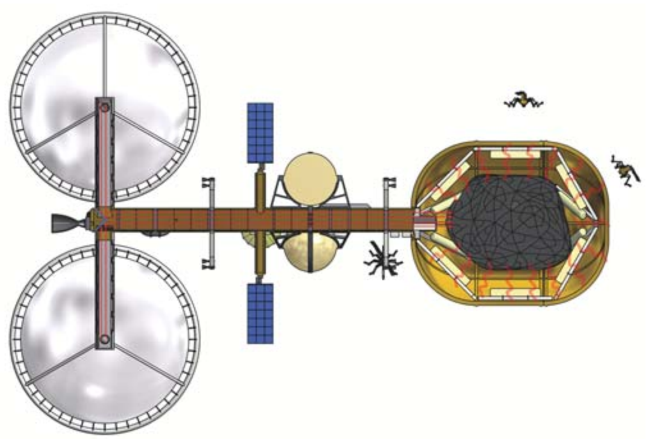
Astrotecture™ Projects for NASA

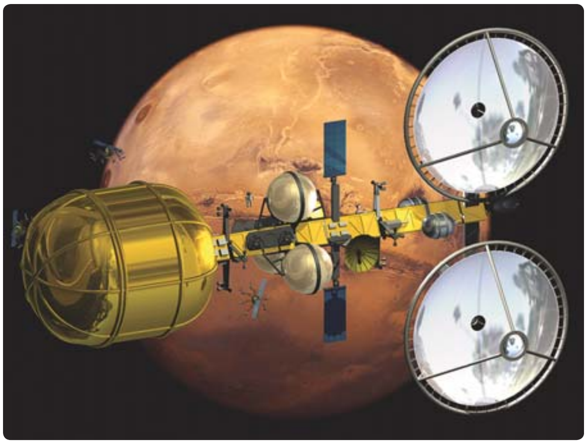


Space Architecture comprises the theory and practice of designing space living and working environments, including human spacecraft, space habitats and other craft accommodations for extreme environments.[1] These environments extend from earth orbit to the Moon, the asteroids, Mars and its moons and beyond throughout our solar system, and eventually to exoplanets in other solar systems. At its core, Space Architecture necessarily involves physical problem solving, which enables the discipline to address a range of other design issues such as robotic space operations, space construction and life support systems.[2]

Astrotecture™, Robotic Asteroid Prospector (RAP), 2012–13
opposite: Prospector operations to capture and mine an asteroid: (1) Approach asteroid, match speed and rotating rate; (2) Capture asteroid within linkages; (3) Inflate air bags to constrain asteroid (notional concept); (4) Close containment then mine asteroid.

below: Longitudinal section through the Robotic Asteroid Prospector showing the distribution of 2,500 degrees Kelvin concentrated sunlight from the solar concentrators to the engine between them, and then forward through the centre truss to the mining operations where it provides process heat.





Robotic Asteroid Prospector (RAP)
Astrotecture's NASA-funded RAP project focuses on developing a robotic asteroid-mining mission that can lead to deep space exploration capabilities for human crews.[3] The central objective of Phase 1 was to determine the feasibility of mining asteroids based on economic, technical and scientific considerations leading to the conceptualisation of initial robotic and, later, human asteroid-mining missions.

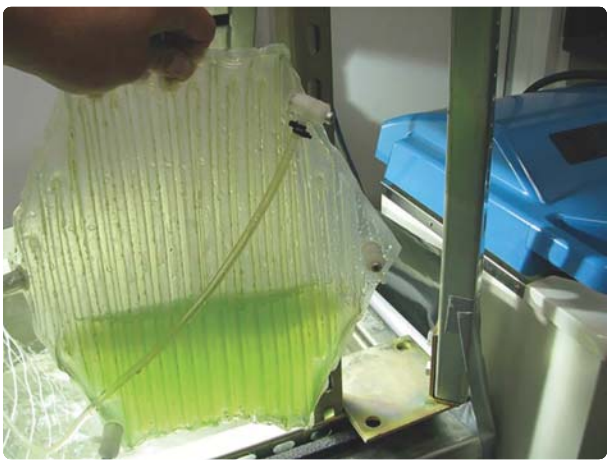
The three main design drivers for the Robotic Asteroid Prospector mission architecture were: the type of propulsion system used spacecraft – the team selected a solar-thermal engine; the Earth–Moon orbital location from where the vehicle departs and returns – here the team selected the Earth-Moon Lagrange Point 2 (EML2) point on the far side of the Moon from the Earth, on the axis from the centre of the Earth to the centre of the Moon; and the source of the propellants – water was selected as the most abundant and easy-to-process fuel available in the vast reaches of the asteroid belt between Mars and Jupiter, and among near-earth asteroids.

above: The RAP near Mars as it approaches the inner moon Phobos. Flying around the RAP spacecraft are 'spider' extraction robots with their photovoltaic panels extended, and a space-suited astronaut just forward of the light-gold-coloured water tanks.

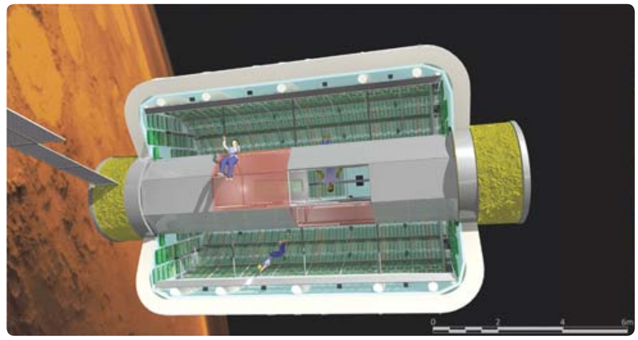
Water Walls Life Support Architecture

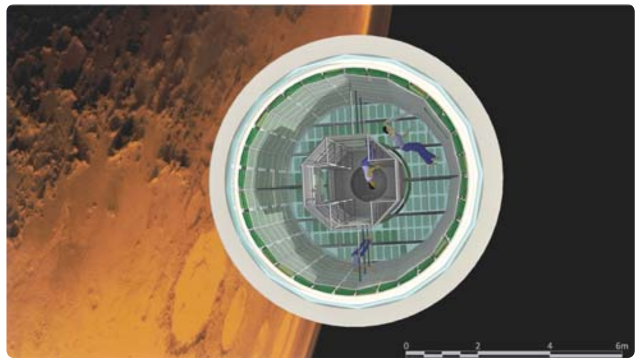
When fully developed, Astrotecture's Water Walls, also funded by NASA, will provide the complete suite of functions as current environmental control life support systems (ECLSS), but will do so with greater reliability, lower cost and the additional benefits of providing radiation shielding, food production and reuse of some of the typical waste streams. The key to achieving this higher level of reliability comes through the application of simple, inexpensive, passive components with massive redundancy.[4]

NASA, Experimental algae growth bag, Bioengineering Laboratory, NASA Ames Research Center, California, 2011
The algae growth containers can come in a wide variety of materials, shapes and sizes.



The key to achieving this higher level of reliability comes through the application of simple, inexpensive, passive components with massive redundancy.





The key unit is the osmotic membrane bag, an inexpensive polyethylene envelope that contains one or more membranes.[5] Because the membrane system is mainly passive, it is less complex, has fewer different parts, and is not subject to the same level of risk from mechanical failure as conventional ECLSS hardware. Instead of the conventional mode of driving the mechanical systems to failure, then repair or replacement, Water Walls plans the predictable and graceful degradation of its components, allowing scheduled cleaning, reuse or reloading. A major advantage of its architecture is that it provides radiation shielding that is 'non-parasitic': it performs the life support functions while also providing radiation shielding.[6]

Astrotecture™, Water Walls Life Support Architecture, 2012–14
top: Longitudinal section through a TransHab-type inflatable module, showing the centre functional core and Water Walls algae bags installed around the perimeter of the habitable volume.

bottom: Transverse section through a Bigelow Aerospace 330 TransHab-type module in which Water Walls air revitalisation bags line the inner circumference and endcaps. The Water Walls concept can adapt to habitats in pressurised modules of any shape, size or dimensions.

Integrated Habitat and Rover

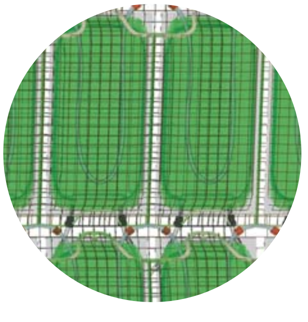
The Space Studies Department at the University of North Dakota invited Astrotecture to serve as a consultant for its NASA Experimental Program to Stimulate Competitive Research (EPSCoR)-funded project entitled 'Integrated Strategy for the Human Exploration of the Moon and Mars'. The project consists of research and design for a simulated lunar/Mars surface habitat with an inflatable envelope and a pressurised rover simulator. The rover incorporates a pair of suitports that allow safe access to the externally mounted spacesuits.

One product of this effort was the technical paper 'Mockups 101', which won the AIAA Space Architecture Best Paper Award presented at the American Institute of Aeronautics and Astronautics Space 2013 Conference and Exposition in San Diego. 'Mockups 101'[7] defines the relationships among the life safety, building and engineering codes that apply to enclosed and confined habitat simulators with particular reference to the technology-readiness levels that a habitat analogue can achieve. ⌀

Astrotecture™, Water Walls Life Support Architecture, 2012–14
Water Walls air revitalisation algae bags.

below left: The input and output tubing (with the black fittings) at the bottom connect to each side of the internal membrane and the thermal control loop (with the red fittings) enters the top of the bag.

below right: Detail of how the algae bags mount to a mesh screen on the space habitat wall.



Notes

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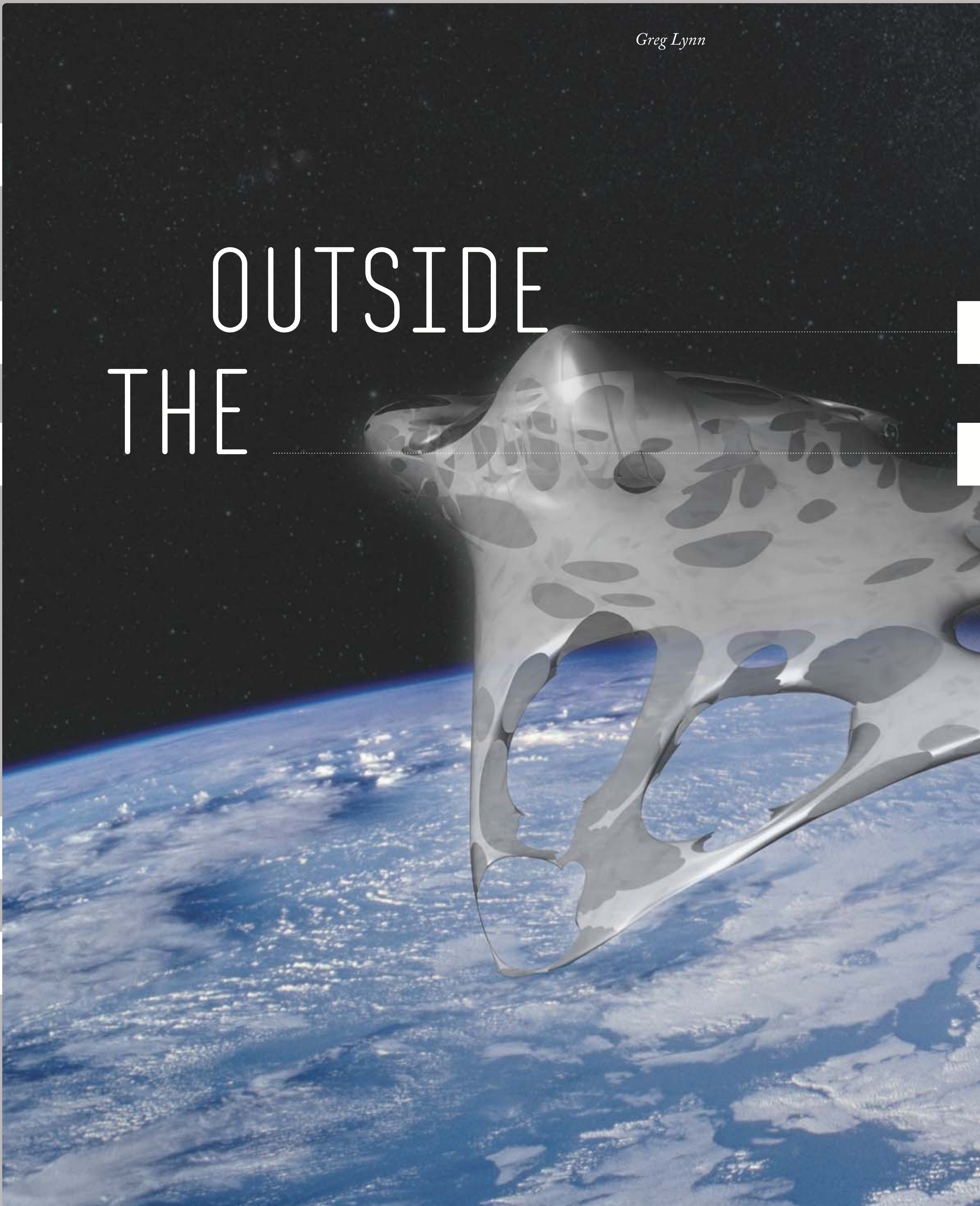
5. Marc M Cohen, Renée L Matossian, Rocco L Mancinelli and Michael T Flynn, 'Water Walls Life Support Architecture', *Proceedings of the 43rd AIAA International Conference on Environmental Systems* (Vail, CO), American Institute of Aeronautics and Astronautics, (Reston, VA), July 2012, p 5.
6. Jack Miller and Marc M Cohen, 'Water Walls Radiation Shielding: Preliminary Beam Testing of Fecal Simulant', *Proceedings of the 44th AIAA International Conference on Environmental Systems* (Tucson, AZ), American Institute of Aeronautics and Astronautics (Reston, VA), July 2014, pp 6–9.
7. Marc M Cohen, 'Mockups 101: Code and Standards Research for Space Habitat Analogues', *Proceedings of the AIAA 2012 Space Conference and Exposition* (Pasadena, CA), American Institute of Aeronautics and Astronautics (Reston, VA), July 2012.

University of North Dakota Space Studies Department and Astrotecture™, Pressurised rover analogue simulator, Grand Forks, North Dakota, 2014
The habitat hatch-berthing port can be seen on the left side, with two 'suitports' mounted at the rear.

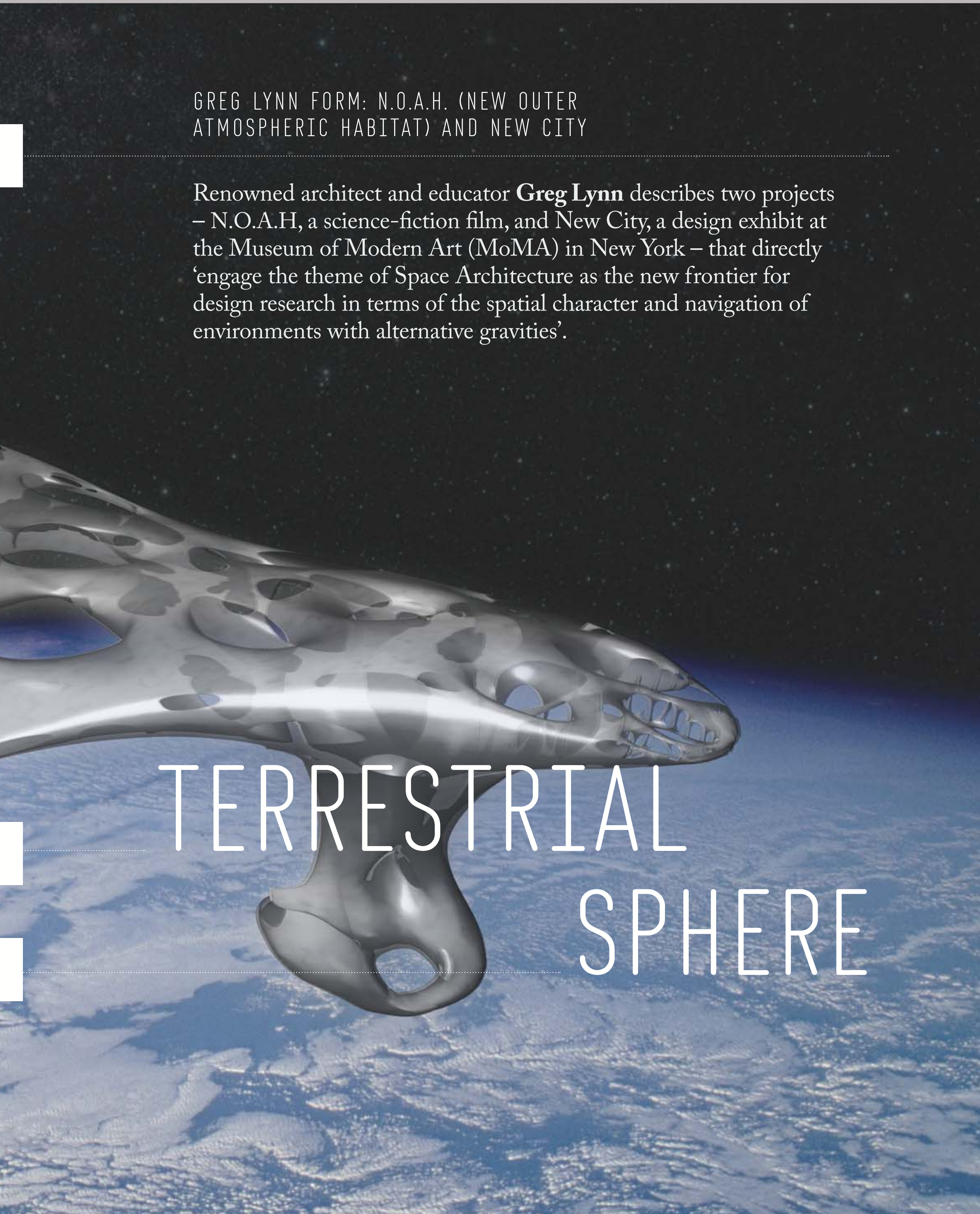
Greg Lynn

OUTSIDE THE



GREG LYNN FORM: N.O.A.H. (NEW OUTER ATMOSPHERIC HABITAT) AND NEW CITY

Renowned architect and educator **Greg Lynn** describes two projects – N.O.A.H, a science-fiction film, and New City, a design exhibit at the Museum of Modern Art (MoMA) in New York – that directly 'engage the theme of Space Architecture as the new frontier for design research in terms of the spatial character and navigation of environments with alternative gravities'.



TERRESTRIAL SPHERE

For decades, through books and texts, I have been involved in developing new models of gravity for use by architects – models that involve bodies in space,[1] differential gravities,[2] multiplicitous and inorganic bodies,[3] and other concepts that do not reduce structure and space to a simplified vertical load path to a flat ground. These ideas have always been intended for use today, on Earth, as alternatives to the simple story that architecture tells of static objects with vertical forces perpendicular to the ground. However, several years ago I was approached to design outside the terrestrial sphere.

The first instance was a planetary-scale environment for a science-fiction film, and soon after came the commission for a Web-based virtual environment that designs visualisation, architecture, simulation, data and experience for a community that includes the entire population of the world in a malleable virtual city. These two projects – N.O.A.H. (New Outer Atmospheric Habitat) (2006) for the film *Divide* (by Jörg Tittel and Ethan Ryker) and New City for Paola Antonelli's 2008 'Design and the Elastic Mind' exhibition at the Museum of Modern Art (MoMA), New York – engage the theme of Space Architecture as the new frontier for design research in terms of the spatial character and navigation of environments with alternative gravities.

Greg Lynn FORM, N.O.A.H. (New Outer Atmospheric Habitat) renderings, 2009
opposite: Microclimates within the pockets and voids create a diverse environment that is of the Earth, but beyond.

previous spread: N.O.A.H.s are metropolis-scale space stations that function outside of gravity-driven architectural constraints.

N.O.A.H.

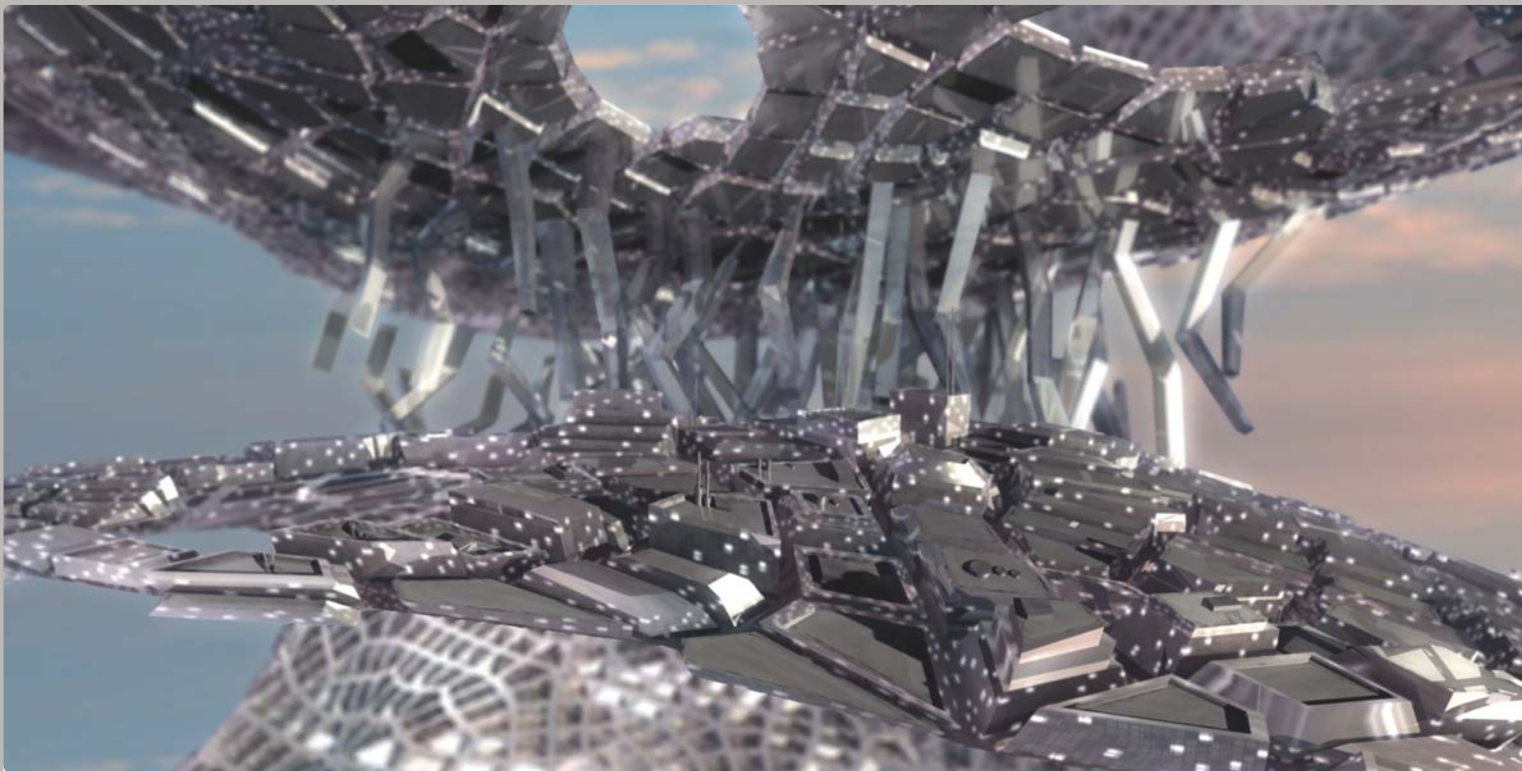
The design of the planet-scale colony for *Divide* begins with an acknowledgment of and departure from the illustrations for Princeton professor Gerard O'Neill's report on the 10-week study he spearheaded at the NASA Ames Research Center in Mountain View, California (1974),[4] where engineers, sociologists, architects and astrophysicists were asked to envision colonies that would orbit the Earth, such as Bernal spheres, cylinders and tori. These proposals were rendered by industrial illustrator Rick Guidice and scientific and astrological illustrator Don Davis. However, where these proposals from the mid-1970s used rotation to simulate degrees of gravity from centre to periphery through centrifugal force, in 2006 N.O.A.H. is composed of topological layers whose inner surfaces are occupied perpendicular to the normal vector of a polygon oriented coplanar to the surface rather than perpendicular to the centre point of a rotating sphere or torus, or the central axis of a rotating cylinder.

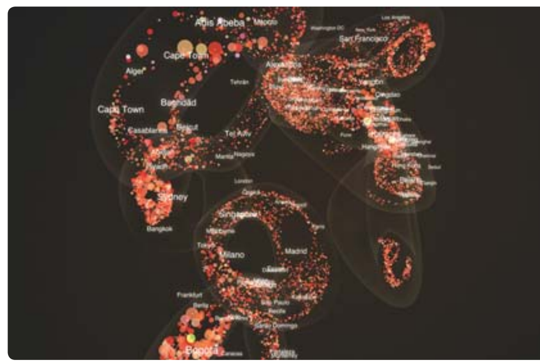
The design is driven by a narrative that fuses literature, architecture and social commentary where the habitat is a central character in the screenplay. The cinematic work is geared towards the general public as a high-concept science-fiction allegory addressing sociopolitical mores that shape our world and future. The four N.O.A.H.s in the film are multi-oriented, porous, city-scaled, man-made space stations housing millions. They are designed to take advantage of gravity-free orientation and, much like a cellular or bacterial space that is so small that gravity plays little role in interior orientation, they are riddled with open spaces and microclimates that are directly transplanted from Earth. It is a design concept that combines architecture, technology and terrestrial nature to create a new ideal of living space; one not bound by planar surface.

From a distance, N.O.A.H. resembles a single vast discrete shape, but from closer observation it becomes an amalgamation of mutable and modular cellular pockets. These cells create a variety of structural layers similar to a coral reef, and read as chambers and volumes within and when intersected with the outer skin, as crater-like openings that bring light and air to the interior. The design and technology of the N.O.A.H.s in the film is the basis for the sci-fi social and political thriller that emerges between the inhabitants of the N.O.A.H.s and the inhabitants of Earth.


GREG LYNN

Greg Lynn FORM, New City and N.O.A.H. (New Outer Atmospheric Habitat), 'Other Space Odysseys', Canadian Centre for Architecture (CCA), Montreal, Canada, 2010
The exhibition featured 3D-printed acrylonitrile butadiene styrene (ABS) models of both the New City manifold and the N.O.A.H. space stations.





New City

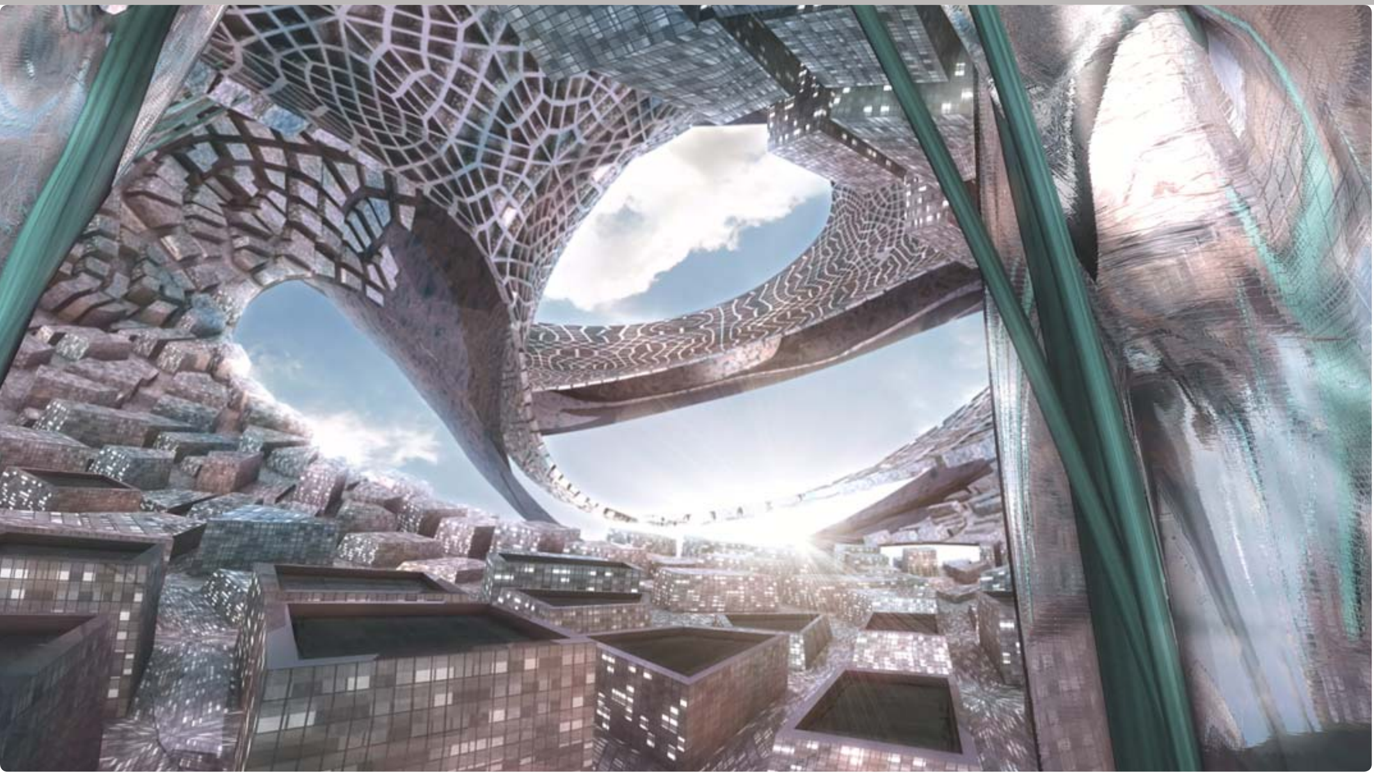
In 2008, when film production designer Alex McDowell, Peter Frankfurt (founding partner of Imaginary Forces) and our office were commissioned by MoMA's curator of architecture and design Paola Antonelli to design an urban online space of interaction for her 'Design and the Elastic Mind' exhibition, we quickly defined the project as New City. As an acknowledgment of Google Earth that uses a globe to organise interactions and spatial geography online, we too began with an orrery-like model of Space. Like an online database of what later has become 'big data', New City is a place of perpetual transformation and self-generation that reflects life on Earth. However, unlike the familiar globe, its urbanism engages contemporary communication, density, lifestyle and globalism in its very geometry and navigation to propose an alternative urban and architectural space.

Greg Lynn FORM, Alex McDowell and Peter Frankfurt/Imaginary Forces, New City animation stills, 2008
top left: In the world as city, political boundaries dissolve and globalism becomes architectural space.

opposite top: Gravitational control allows for a new interpretation of architecture from the building scale to the urban scale.

above left: New City re-imagines the world as an interconnected manifold.

above right: Adjacencies reflect contemporary communication to create a global urbanism.



New City is designed as a manifold, a surface that forever folds onto itself, capturing endless dimensions of volumentric space, distance, time and adjacency in a manner more consistent with the experience of electronic communication, travel and shipping today, and less reliant on the physical geography of the surface of the Earth. Seven topological manifolds organise the continents of the Earth where locations are mapped onto their folding surfaces. The toroidal manifolds can change size and orientation, one to another, to reflect the personal geographies of whomever is navigating them. The movement and behaviour of user populations are reflected in the dynamic motion of the city in, around and through itself, and the unique social characteristics of the real world are dynamically merged and mixed into new unpredictable syntheses.

A way to experience and populate a new architecture, New City is built to reflect the physical laws of a manifold city in motion. A place like Little Tokyo in Los Angeles or Little India in Singapore, for example, would stretch and align continental surfaces bringing locations adjacent and intersected without reference to the surface of the Earth, as is currently the case in online browsers. This departure from the globe and the orrery and mappa mundi rooms from the Renaissance in favour of a more robust spatial and mathematical model of Space helps to align New City with the experience of space and place today, online and incommunicado.

While neither N.O.A.H. nor New City are proposed as Space Architecture per se, both projects engage spatial paradigms for experience and navigation that rely on alternative models of gravity of the type that might be relevant to architects who leave the terrestrial sphere.

Greg Lynn FORM, Alex McDowell and Peter Frankfurt/Imaginary Forces, New City installation, 'Design and the Elastic Mind', Museum of Modern Art (MoMA), New York, 2008
above bottom: The installation featured an architecturally scaled immersive media environment that served as the trailer for the concept of a living virtual world that is parallel and simultaneous to our own.

Notes
1. Greg Lynn, *Folds, Bodies and Blobs: Collected Essays*, La Lettre Volée (Brussels), 1998.
2. Greg Lynn, 'Differential Gravities', in John Rajchman and Greg Lynn (eds), *ANY 5: Lightness*, March/April 1994.
3. Greg Lynn, 'Multiplicitous and Inorganic Bodies', *Assemblage*, 19, 1992, pp 33–49.
4. Gerard K O'Neill, 'The Colonization of Space', *Physics Today: Colonies in Space*, 27(9), 1974, pp 32–40.

Ondřej Doule

GROUND CONTROL

SPACE ARCHITECTURE AS DEFINED BY VARIABLE GRAVITY

Ondřej Doule/Space Innovations, Silverbird v2 rocket plane, 2011
The Silverbird in suborbital flight. Hypergravity and microgravity interior architecture provide maximum safety.

Silverbird v2 depicted during take-off. Passenger requirements played a main role in the design of the rocket plane flight profile and the whole plane configuration.

The research of architect and educator **Ondřej Doule** focuses on human–system integration in spaceship cockpits and space station interiors. Here he describes how his interest in Space Architecture has been fuelled and defined by gravity or the lack of it: gravity being a constant on Earth, but a constant variable in Space.

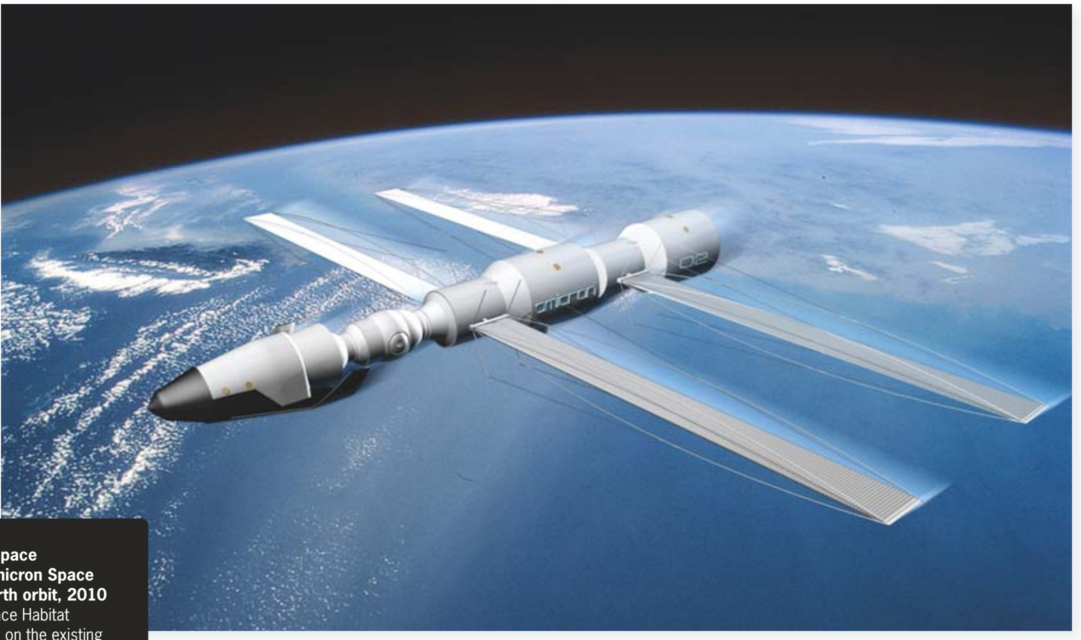
Many of the variables that drive the design concepts of 21st-century architects are subject to personal preference. With current technologies, computing capabilities and construction processes there appear to be minimal technological restrictions in architectural design. What are the inputs to our design intentions that tell us which architectural form, style or structure we should use and how human–system integration should be performed? Is architecture so complex that it still cannot be defined and guided by any generic design principles?

If we place architecture in an unfamiliar extreme environment, we will immediately see what system design aspects are key. Designing architecture for terrestrial environments is complicated, but stepping into an area of variable micro- or reduced gravity in Space adds another, still unexplored level of complexity.

My own interest in variable-gravity environments began in tandem with my architectural studies. While studying at the Faculty of Architecture at the Czech Technical University in Prague, I undertook research at the International Space University in France. This interest in Space Architecture, as defined by gravity or the lack of it, is something I have continued to pursue in my work at the Space Innovations design research studio I founded in 2011, as well as at the Human-Centered Design Institute at Florida Institute of Technology in the US, supported by the knowledge base of the American Institute of Aeronautics and Astronautics (AIAA) Space Architecture Technical Committee.

Space Architecture as Redefined by Team XI

A general framework for the new field of Space Architecture was launched in 2002 by Team XI, which set itself up as a continuation of Team X. Centred around the International Congress on Modern Architecture (CIAM) and major personalities of 20th-century architecture,



Ondřej Doule/Space Innovations, Omicron Space Habitat, low earth orbit, 2010
The Omicron Space Habitat concept is based on the existing Russian Salyut and Zvezda modules designed for the Proton launcher.

such as Le Corbusier and Sigfried Giedion, Team X was founded in 1928 and disbanded in 1958. Team XI's aim was to redefine Space Architecture, in the forward-looking spirit of its dynamic predecessor, as:

> the theory and practice of designing and building inhabited environments in outer space, responding to the deep human drive to explore and occupy new places[1]

Furthermore, Team XI revived the CIAM tradition by establishing a team of experts that meets to discuss global societal and technological evolution and identify the needs that should be addressed by architecture on a strategic level, while also providing general ontological guidance. The definition of the new field of Space Architecture points out four main architecture ordering principles, which are not inherent to traditional perception of architecture: duration (of the architecture); speed (of the system in which the architecture is placed relative to reference system); pressure (of the surrounding environment); and gravity (of the system and the environment), and also brings to the fore the important question as to whether terrestrial architecture belongs to Space Architecture or whether these two should be kept separated.

Naturally, Space Architecture deals with the environment in a broader and deeper sense, noting also the gravity differences. Terrestrial architecture is 'used to' one type of gravity and all empirical knowledge and standards are related to it. This main ordering principle 'gravity' that is relatively constant on Earth becomes one of the most important variables in Space and therefore also an important driver in Space Architecture projects.

The first space stations provided great hands-on experience that was unknown to humans until the 20th century. The American Skylab (1973–9)[2] and Russian Salyut (1971–82),[3] the first space habitats created by teams of aerospace engineers, ergonomists and designers, proved that no floor or ceiling is needed in microgravity, and that large volumes may be dangerous when stuck in the centre unable to push oneself off a wall to move around. Nevertheless, the ceiling-floor design prevailed in early habitats. This no-gravity spatial disorganisation was well understood by Slovenian rocket engineer Herman Potočnik ('Noordung') (1892–1929). It is said that his pseudonym Noordung originates from the state in which objects behave in microgravity that can be considered as 'no-order' – no gravity. His revolutionary work on orbital[4] stations from the beginning of the 20th century became the basis even for German rocket engineer and space architect Werner von Braun and his S1 (1946) and S2 (1955) stations that further inspired Arthur C Clarke's famous space station in the film *2001: A Space Odyssey* (1968), produced and directed by Stanley Kubrick, and numerous space colonies concepts. While Potočnik provided

Ondřej Doule/Space Innovations, Lunar Base 10 (LB10), Moon north pole, 2011
Permanent lunar settlement deployed from one launcher and covered with sintered regolith shell in the Lunar Baroque style.

the first space architecture insight in defining order in microgravity, the rocket engineering and humankind's expansion to space had been earlier predicted and visualised also by novelist Jules Verne (1828–1905) and by Russian professor and inventor of the 'ideal rocket equation', Konstantin Tsiolkovsky (1857–1935).

Spaceships: Variable Gravity Levels

Gravity is the main ordering principle in architecture.[5] Orbital space architecture, which must deal with microgravity and artificial gravity, is probably the most challenging environment to comprehend for the implementation of architectural design. One of the biggest problems, however, is in designing for an environment of rapidly changing gravity levels in spaceship interiors for journeys from the Earth's surface into orbit, atmospheric entry or interplanetary travel, as a cognitive and physical support to human activities.

The environment inside these spaceships includes variable gravity values that span from hypergravity to microgravity. While the hypergravity values are usually of temporary character (seconds to minutes), microgravity may be longer term (minutes, hours or days). Interiors affected by such a variety of gravity levels require consideration of safety for all activities in different G levels and also variable G directions.[6] Current NASA, GOST and ISO standards provide only basic guidance and frameworks for variable gravity environment design that still count on human adaptation during space flight.

Orbital Architecture: The Microgravity Challenge

A microgravity environment is one of the most interesting in the universe from an architectural point of view, lacking ceiling and floor perception and requiring strong orientation reference frames for human motion. All of the stations and habitats that have so far been launched, tested and flown in Space have been influenced by one main driver: terrestrial gravity. There is simply no way to simulate microgravity on Earth for sufficiently long to replicate internal habitat operations in weightlessness. An environment that lacks the main ordering principle and its organisation does not necessarily require a horizontal floor or other relics of humans' bounds to the Earth.

So how should we approach microgravity architectural design? Each orbital structure has a different function and is bound to certain orbit and/or distance travel capacity. Orbital mechanics will tell us where the front, aft, starboard and port sides of the system are, where to place ports, docks, hatches and windows, and how to orient photovoltaic panels and radiators for highest efficiency. The structural geometry is driven by maximum efficiency regarding internal overpressure relative to external vacuum, resulting in spherical, cylindrical and toroidal shapes. In the interior we need to understand human–system integration, functions and human motion that is not constrained by a Cartesian

system.[7] Standards such as NASA STD-3001, NASA/SP and others currently provide us with basic volumetric, geometrical and interface design guidance for the complex microgravity environment.

On Celestial Bodies: Lunar and Martian Architecture

Although the microgravity environment is a challenge for designers, it is important to master and implement well in systems such as space stations and spaceships in earth orbit or en route to the Moon and Mars. These celestial bodies, in the closest vicinity of Earth, are most interesting in terms of human space flight exploration, and provide, similarly to Earth, one vertical force (gravity acceleration) equivalent to their mass that helps organisation, layout and coordination of the artificially built environment. The Cartesian system is again applicable, but the entire structure is subject to many more different environmental properties and loads than on Earth.

The Apollo missions (1967–72) proved that human presence on the Moon is possible, though scientists identified major threats to surface operations from lunar dust and lethal radiation, which are less of a risk on the Martian surface. For architects, constant gravity levels are much more intuitive, as will be lunar and Martian architecture. One-sixth on the Moon and one-third of Earth's gravity on Mars possess an ordering principle that is similar to the terrestrial environment. Nevertheless, the differences in the gravity levels introduce completely new environments that architects are not intuitively familiar with. Put simply, objects on the Moon and Mars will weigh x-times less, hence much thinner, lighter structures and larger spans will be possible. Fortification against ionising radiation and meteorite projectiles on the Moon requires walls at least 2 metres (6.5 feet) thick[8] to protect inhabitants, similarly to the fortresses from the Baroque age on Earth. Lunar Baroque fortification may create a natural link with humankind's architectural and cultural achievements on Earth, reviving them on the Moon in an integrated and noble style.[9]

On the other hand, architecture built on the distant Mars may require higher levels of autonomy, integration and prefabrication, including self-assembly of the first habitats. Structures on Mars do not have to be as heavily shielded as on the Moon, and similarities with terrestrial construction processes will occur once the first auto-habitat is deployed and fully operational.[10]

The Mission

Space Architecture has still to define the main standards for lunar and Martian architecture or find parametric translation of terrestrial standards to different gravity environments. Reduced gravity has a significant impact on vertical motion, ergonomics and vertical structures, loads,

Ondřej Doule/Space Innovations and A-ETC, Martian Base 10 v2 (MB10), Olympus Mons, Mars, 2010
opposite: A permanent settlement at the foot of a Martian volcano, MB10 is deployed from one module and intended to serve as a first base before structures from local materials are built.

SPACE ARCHITECTURE HAS STILL TO DEFINE THE MAIN STANDARDS FOR LUNAR AND MARTIAN ARCHITECTURE OR FIND PARAMETRIC TRANSLATION OF TERRESTRIAL STANDARDS TO DIFFERENT GRAVITY ENVIRONMENTS.

spans and foundations. Human motion may require more vertical clearance, and staircases with fewer steps than those on Earth that are calculated according to, for example, the Lehmann and Engelmann formula.[11] The ceilings and the steps will simply be higher.

Extension of NASA and GOST standards and the development of ISO standards for extraterrestrial designs within industrial collaborations and education are essential. However, the generation of empirical knowledge regarding safe and effective human–system integration and design still requires an increased human presence in outer space. ⌂

Notes

1. Jan Osburg, Constance Adams and Brent Sherwood, 'A Mission Statement for Space Architecture', Society of Automotive Engineers, Inc, 2003: http://papers.sae.org/2003-01-2431/.
2. David J Shayler, *Skylab: America's Space Station*, Springer Praxis Books/Space Exploration (Berlin, Heidelberg, New York), 2001.
3. Grujica Ivanovich, *Salyut – The First Space Station: Triumph and Tragedy*, Springer Praxis Books/Space Exploration (Berlin, Heidelberg, New York), 2008.
4. Herman Potočnik, *Das Problem der Befahrung des Weltraums – der Raketen-Motor*, Richard Carl Schmidt & Co (Berlin), 1929.
5. Ondřej Doule, 'Space Architecture: Theory and Educational Strategy', *Proceedings of the AIAA 40th International Conference on Environmental Systems* (Barcelona), American Institute of Aeronautics and Astronautics (Reston, VA), 2010.
6. Ondřej Doule, 2008, 'Passenger Safety on Personal Spaceflight – Spacecraft Interior Concept Design – Silverbird', *Proceedings of the 59th International Astronautical Congress* (Glasgow), International Astronautical Federation (Paris), 2008.
7. Ondřej Doule, Vratislav Šálený, Benoît Hérin and Tomáš Rousek, 'Omicron Space Habitat: Research Stage II', *Acta Astronautica*, 70, 2011, pp 139–58.
8. Haym Benaroya, *Lunar Settlements*, CRC Press (London and New York), 2010.
9. Ondřej Doule, Emmanouil Detsis and Aliakbar Ebrahimi, 'A Lunar Base with Astronomical Observatory', *Proceedings of the AIAA 41st International Conference on Environmental Systems* (Portland, OR), American Institute of Aeronautics and Astronautics (Reston, VA), 2011.
10. Ondřej Doule, 'Mars Base 10: A Permanent Settlement on Mars for 10 Astronauts', *Proceedings of the AIAA 39th International Conference on Environmental Systems* (Savannah), American Institute of Aeronautics and Astronautics (Reston, VA), 2009.
11. The sizing of stairs in terrestrial gravity can be calculated according to the Lehmann and Englemann formula where 630 mm is the average length of the human stride, *h* is the rise (height of the step) and *b* is the breadth of the step : $2x\ h+b=630$. See G Lehmann and B Engelmann, 'Der zwechmassigste Bau einer Treppe', *Arbeitsphysiologie*, 6, 1933, pp 271–82.

PROJECTING INTO SPACE

INTERNATIONAL STUDENT PROJECTS

As Guest-Editor **Neil Leach** highlights, designing for Space vacillates between two distinct approaches, 'the mercilessly functional or the indulgently fantastic' with little middle ground. Here he features the work of students internationally that embody these two discrete strands, from RMIT University in Melbourne, California Polytechnic State University (Cal Poly), the University of California, Los Angeles (UCLA), University of Applied Arts Vienna, University of Southern California (USC), Dessau Institute of Architecture (DIA) in Germany, and the Sasakawa International Center for Space Architecture (SICSA) at the University of Houston.

Architecture, for Roland Barthes, is always a combination of utopian dreaming and functional convenience. But in the context of Space Architecture we may need to rethink this relationship, in that the conditions of operating in Space can often prove extremely limiting. On the one hand, this situation encourages tightly controlled projects responding very precisely to their constraints. On the other hand, those very constraints can often prove overly stifling, and promote instead a form of utopian dreaming. As a result, we often find that Space Architecture – whether realised or merely speculative – can be somewhat schizophrenic. Even though ideally it should be a combination of both, Space Architecture often tends towards either the mercilessly functional or the indulgently fantastic. Indeed, this also reflects popular impressions about Space itself. For some, Space is a science-fictional, awe-inspiring world of endless fantasy that fires the imagination. Meanwhile, for those working in the actual space industry it is quite a different matter, and Space is seen as a very exacting environment that demands careful and serious solutions.

Schools of architecture reflect this dilemma. Those connected closely with the space industry tend to promote scientifically rigorous design solutions, while others see in Space Architecture the potential for design speculation. Thus some projects featured here keep rigidly to functional constraints to produce precise and tightly controlled designs, while others pay less attention to such constraints and indulge in a certain degree of whimsy and fantasy. Included among the former are the projects from the Sasakawa International Center for Space Architecture (SICSA) at the University of Houston that hosts the only master's programme dedicated to Space Architecture. A similar approach is taken by the project from the University of Southern California (USC), where Neil Armstrong, the first man to walk on the Moon, was himself a student, and the project from the University of California, Los Angeles (UCLA), whose Ideas campus engages extensively with the space industry, was co-supervised by Brandon Pearce of Space Exploration Technologies Corporation (SpaceX), the space transport services company that was the first private firm to send a spacecraft to the International Space Station). Likewise, the NASA-sponsored project by students from the California Polytechnic State University (Cal Poly) is a serious attempt to rethink the nature of a space habitat. Meanwhile, other projects – especially the extravagant yet inspirational proposals from RMIT University in Melbourne, the University of Applied Arts Vienna and Dessau Institute of Architecture (DIA) in Germany – are more whimsical in nature, and constitute a form of design fiction. Nor should we be overly critical of this. For just as science fiction informs science, so too design fiction informs design. Yet the process also works in reverse, in that just as science informs science fiction, so too design informs design fiction. Put together, then, these projects offer us not only a broad overview of student approaches to Space Architecture, but also a reflection on the nature of Space Architecture itself.

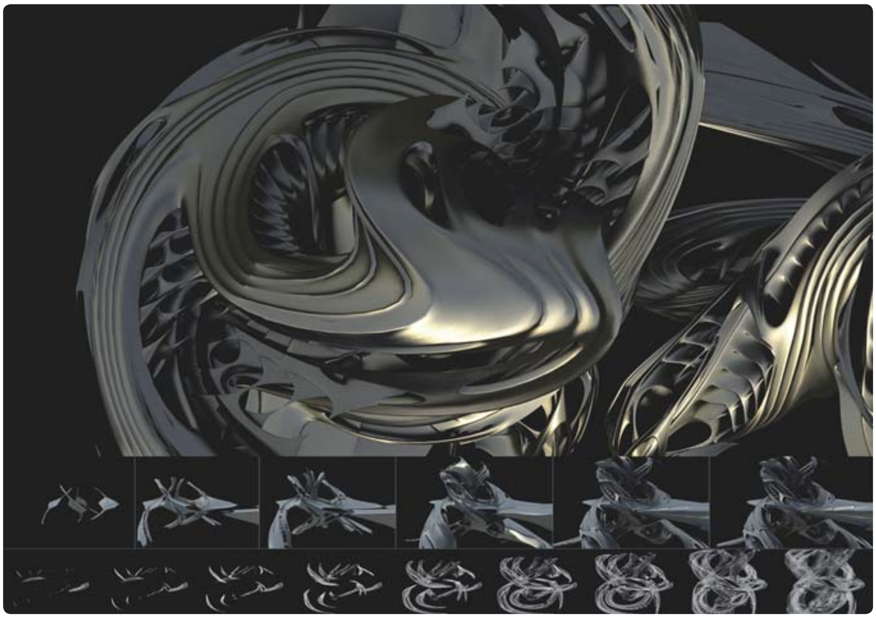
Note
1. Roland Barthes, 'The Eiffel Tower', in Neil Leach (ed), *Rethinking Architecture: A Reader in Cultural Theory*, Routledge (London), 1997, p 174.

ARCHITECTURE IS ALWAYS DREAM AND FUNCTION, EXPRESSION OF A UTOPIA AND INSTRUMENT OF A CONVENIENCE.
– ROLAND BARTHES, 'THE EIFFEL TOWER', 1997[1]

Tropistic Tendencies

This proposal deals with conditions of extreme sunlight versus darkness, and the magnetic forces at play between celestial bodies, all while trying to self-generate gravity within a network of intersecting manifold environments independently housing various programme types. The self-mutating, multifaceted manifold systems are developed on a layered set of rules, bringing about in all scenarios of mutation a symmetry to constantly maintain a continuous loop, and internally subdivided for living spaces, working/research environments, agriculture and solar harvesting. Public spaces and inner landscapes intertwine, forming a continuous flow of circulation throughout the evolving structure – a perfectly balanced organism.

Will Hosikian (tutor: Tom Kovac), MARCH, RMIT University, Melbourne, 2009



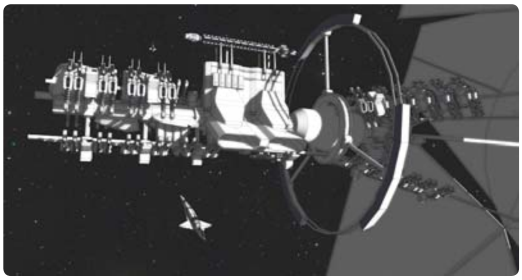
Vertical Habitability Layout and Fabrication Studies

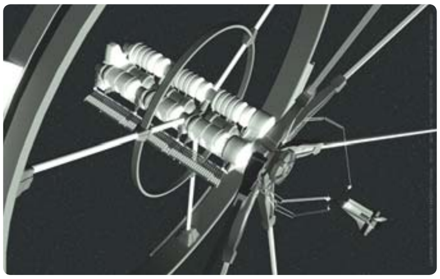
The design challenge of a vertically oriented habitat is to work with the volumetric limitations and 'dynamic envelope', given that deep space habitats must contain everything they need from the start, without resupply. This NASA-sponsored proposal hinges on a building information model (BIM) approach that was leveraged in two principal ways: the first to benefit very long-duration missions by setting up an inclusive model consisting of the usage rate of consumables and their locations in the habitat so that they can be managed dynamically by means of a real-time automated diagnostic; and the second to compare alternative architectural designs in order to find the most elegant engineering/architectural solution within a constraint-driven approach.

Lina Chan, Veronica Hernandez, Patrick Kornman, Andrew Cartwright and Marc Abdelsaeyed (tutor: Michael Fox), MArch/BArch, California Polytechnic State University (Cal Poly), Pomona, California, 2012

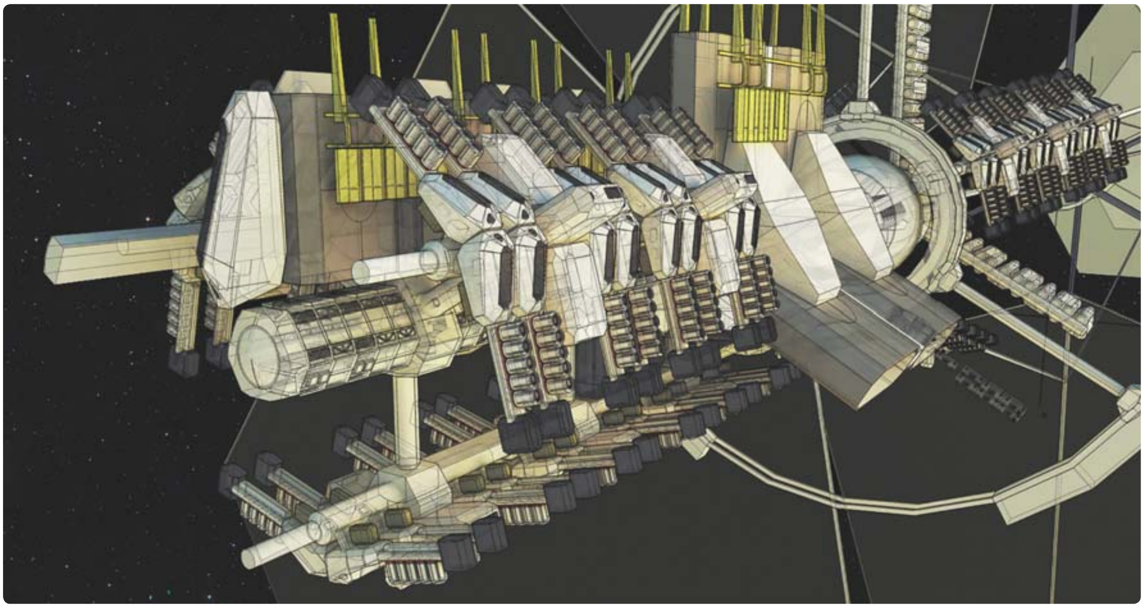
Space-Based Solar Power

This project for a solar power space habitation gathers energy from sunlight in Space and transmits it wirelessly to Earth. A central issue explored was space manufacturing. The premise is that rather than sending a constructed architecture to space, small robotic modules are dispatched that are capable of reproducing through automated fabrication techniques. Such structures can respond in a humanlike way to counteract loads and reduce the amount of materials required. They can also change shape to block sunlight, allow for active ventilation and insulation, and prevent their own degradation. When enough of the architecture has constructed itself with minimal human intervention, humans are sent to inhabit it.



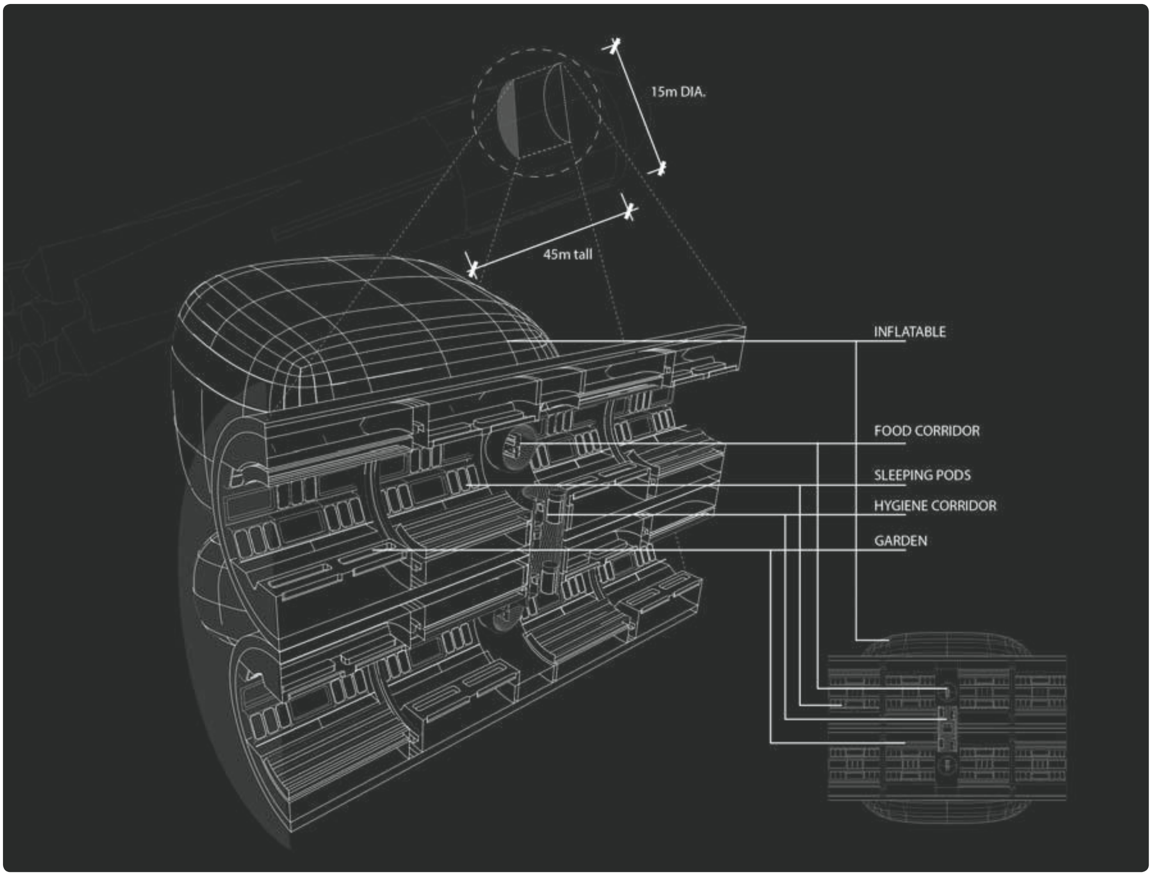


Martin Saet (tutor: Michael Fox), BArch, California Polytechnic State University (Cal Poly), Pomona, California, 2011

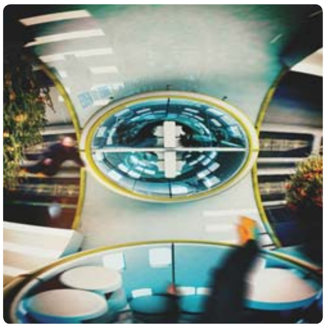


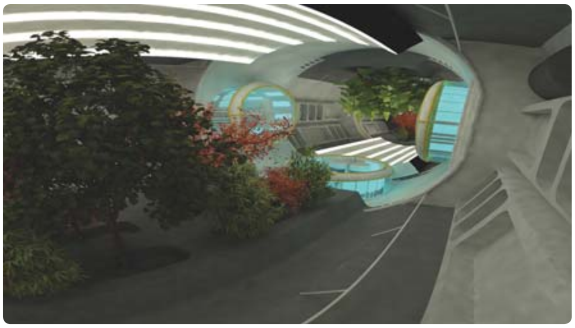
Eden

Working closely with Brandon Pearce of SpaceX, the UCLA team took on the challenge of designing a spatial experience for the inside of SpaceX founder Elon Musk's hypothetical Mars Colonial Transporter for 100 people to travel on a six-month journey to the Red Planet. Eden embraces the ultimate challenge of designing for confined spaces and proposes a multifunctional, compact and deployable structure. Through the arrangement of subdivided, modulated spaces and scheduled time shifts, it addresses the cohabitation and operational needs of the crew and passengers and their desire for privacy. The layout includes four main sectors subdivided into eight chambers, each with essential amenities for a community of 12 travellers.



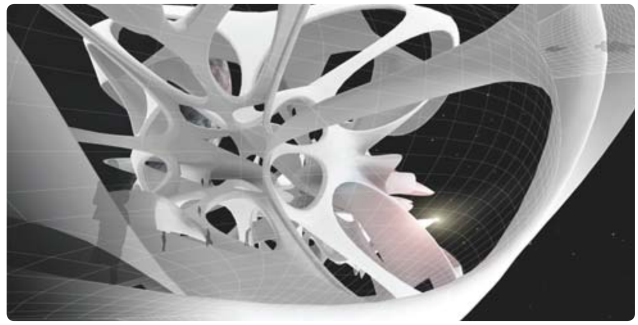
Brandon Harper, Ismael Soto, Oleg Mikhailik and Robert Koshgarian (tutors: Valerie LeBlond and Brandon Pearce), MArch, University of California Los Angeles (UCLA), 2014

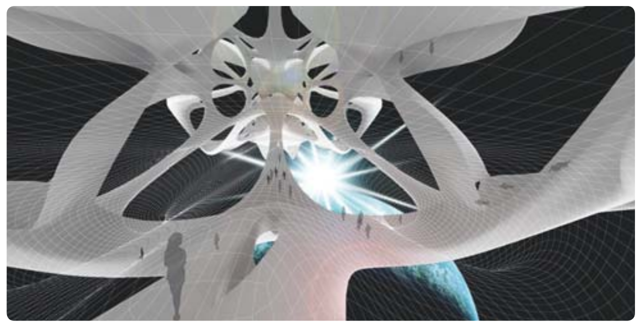




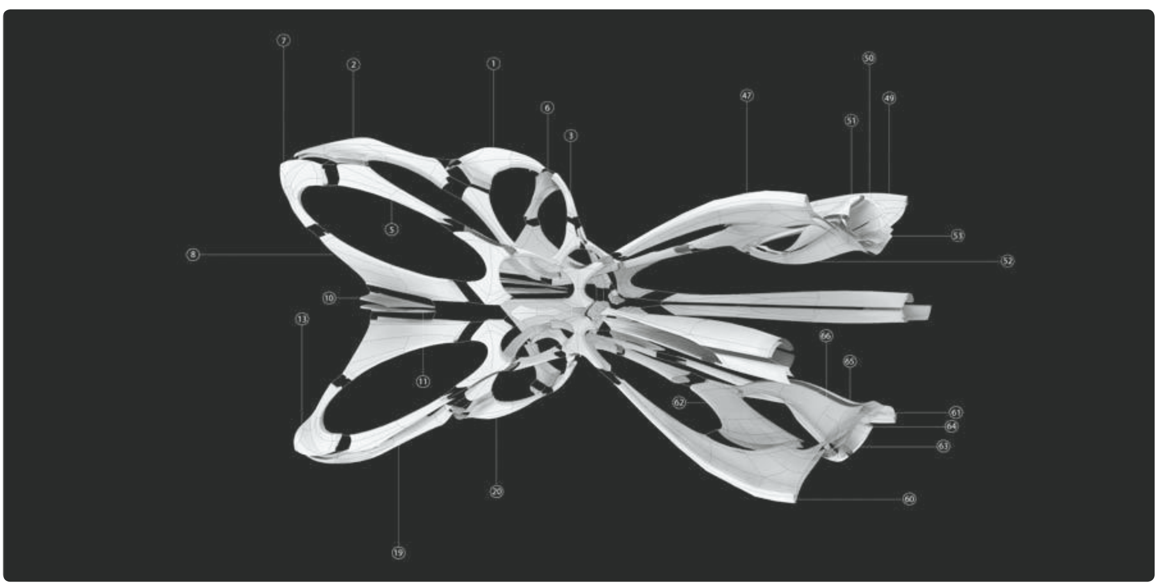
Space Collective

Inspired by spacecollective.org, a community-driven website for the exchange of information and ideas established by Rene Daalder, the Dutch writer, director and pioneer of virtual reality, the project addresses the architecture, landscape and urban constraints of extraterrestrial design. Circular sections define the spatial organisation of the architecture in zero gravity and are developed from biological research into human vertebrae as well as the historic architectural precedent of Andrea Palladio's plan for the Villa Rotonda in Vicenza, northern Italy (1566–92). The combination of soft and hard elements within the organic structure relates to bone and flesh as in the human body. The design explores new horizons within built structures in outer space and generates enticing spatial qualities and enigmatic visual effects in the interior.



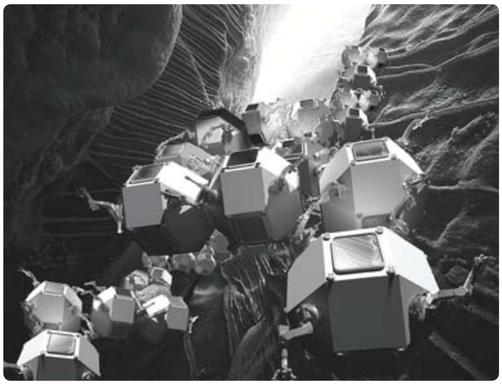


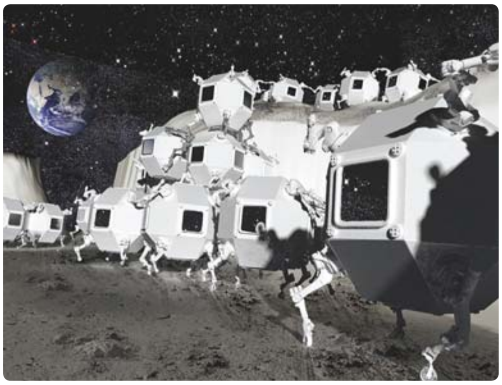
Julia Koerner (tutors: Greg Lynn and Brennan Buck), MArch, University of Applied Arts Vienna, 2007

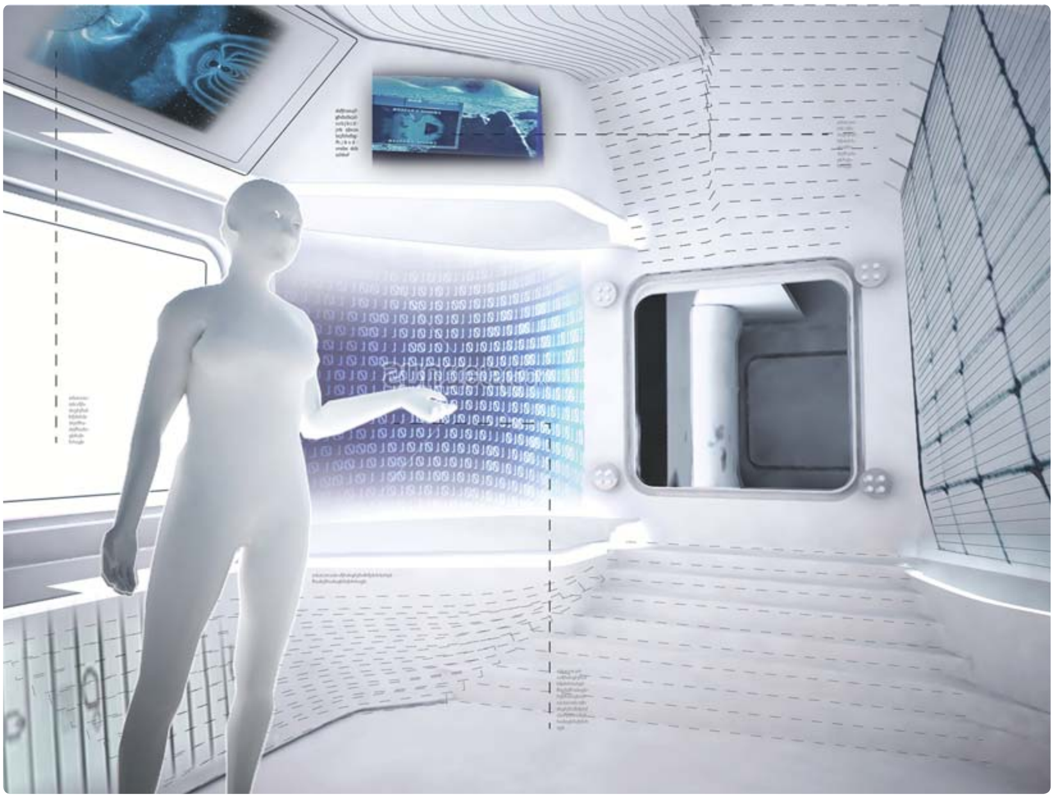


Mobile Intelligent Habitat

This project explores the feasibility of an aggregation of mobile lunar habitats that operate through a form of swarm intelligence as a multi-agent system. The habitats are equipped with robotic arms, through which they are able to clamp themselves together to form an assembly. They are thereby able to aggregate as a swarm in order to clamber over difficult terrain or to climb down lava tubes, the natural formations beneath the surface of the Moon that provide a form of sanctuary from the extreme radiation on the surface.



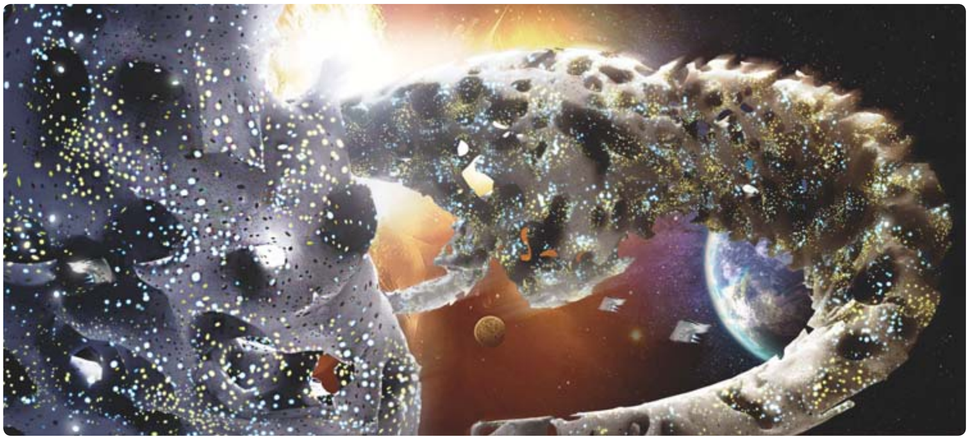




Behnaz Farahi (tutors: Neil Leach, Anders Carlson and Madhu Thangavelu), MArch, University of Southern California (USC), Los Angeles, 2012

RILAO

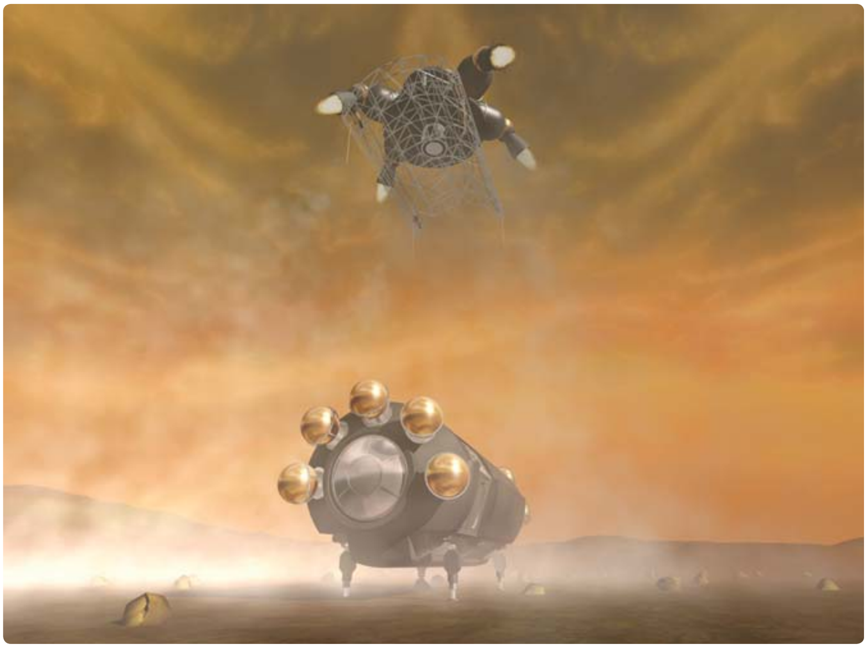
RILAO is a fictional, world-building project, based on the 'genetic DNA' of Los Angeles and Rio de Janeiro, for a space colony situated at the Lagrangian point between the Earth and Moon. Forces of attraction serve not only to maintain the respective position of the colony, but also to produce its form. Magnetic force fields are used to generate the overall form and its protective atmospheres, while the logic of reaction diffusion articulates its internal structure, producing coral-like formations. Magnetic forces and gyroscopes simulate the effect of gravitational forces. The colony is imagined as a contemporary Noah's Arc – a 'seed bank' of DNA – for cloning human beings or even entire planets.



Dimiter Baldzhiev, Jinlin Liu and Islam Sabee (tutors: Neil Leach and Alex Kalachev), Master of Architecture, Dessau Institute of Architecture (DIA), Dessau, Germany, 2014

Mars Project

SICSA's design for a special lander places habitat modules directly on the surface of Mars from above, rather than via the more conventional approach that mounts payloads on landing platforms, which requires them to be offloaded by separate means. The modules and other payloads are lowered using tethers deployed from the hovering 'skycranes' at low altitudes just prior to landing. A similar strategy was independently developed and later successfully demonstrated in order to deploy a NASA Mars rover.



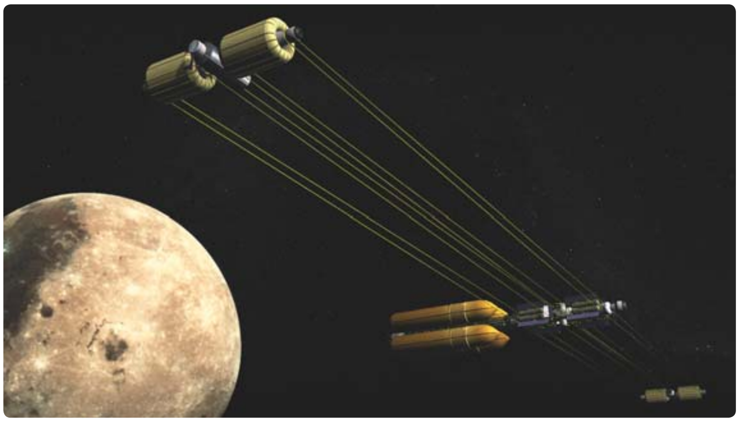
Randy Del Pilar, Andre De Jean, John Odom and Sirleyster Tabangay (tutors: Larry Bell and Olga Bannova), MS Space Architecture, Sasakawa International Center for Space Architecture (SICSA), University of Houston, Texas, 2010–11

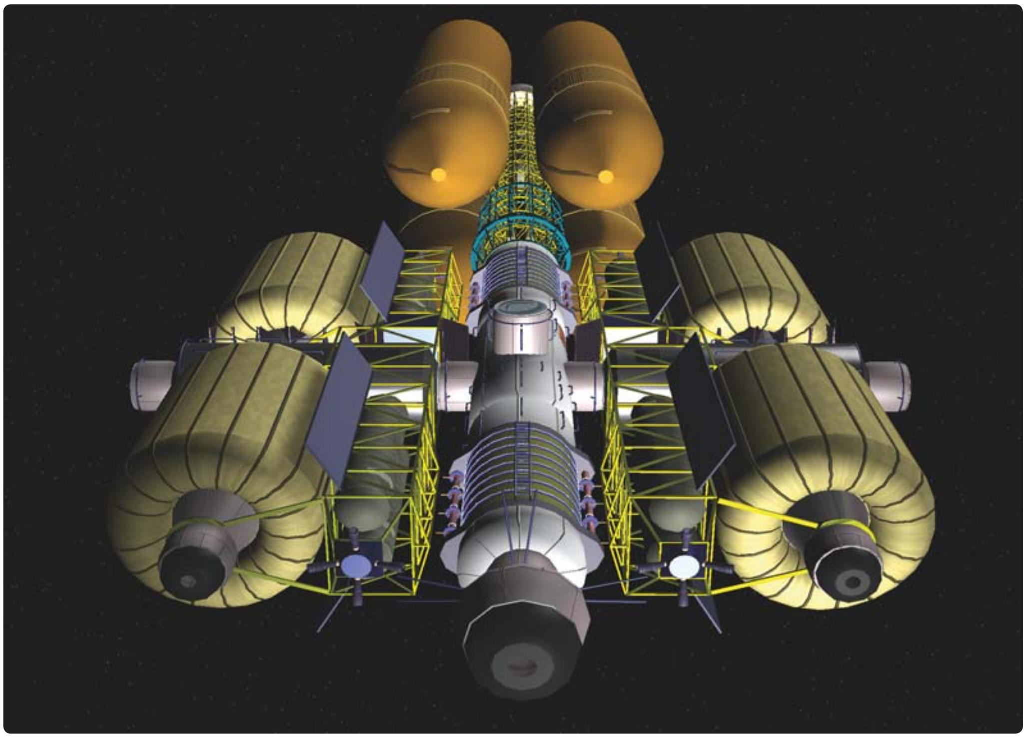
AGSEV

Artificial Gravity Science and Excursion Vehicle

The AGSEV artificial gravity spacecraft uses long tethers to provide the centripetal force necessary to offset crew musculature, cardiovascular and skeletal deconditioning during long-term space missions lasting many months or even years. The tethers avoid the need for very long and heavy physical armatures that would impose enormous launch and in-space assembly difficulties.

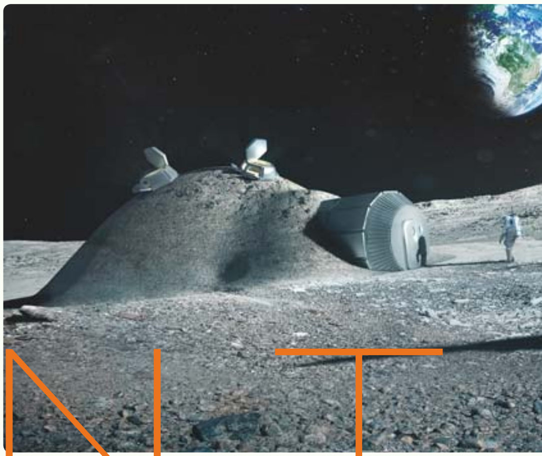
The major elements include a 'hard' central connecting module where crew-transfer vehicle docking occurs, flanked by sets of inflatable modules that provide relatively spacious living accommodation. Tether deployment occurs following launch departure, and they are retracted to reconnect the assembly during orbital course corrections and during near-earth crew exchange manoeuvres.





Devin Johnston, Jacky Lee, David Culp and Heather Stark (tutors: Larry Bell and Olga Bannova), MS Space Architecture, Sasakawa International Center for Space Architecture (SICSA), University of Houston, Texas, 2010–11

3D PRINT SPACE



Enrico Dini, Foster + Partners, Alta SpA and the Laboratorio di Robotica Percettiva (PERCRO)/Scuola Superiore Sant'Anna, D-Shape, 2012
opposite top: Close-up view of structure being printed using D-Shape printing technology.

opposite centre: External view of a moon habitat under construction using D-Shape printing technology.

opposite bottom: View looking over a colony of moon habitats under construction using D-Shape printing technology.

right: View from above of a moon habitat being printed using D-Shape printing technology.

bottom: Cross-section of moon habitat showing internal pressurised volume and printed outer casing.

ING IN

The cost of transporting raw materials into Space is prohibitive – potentially US$2 million for a single brick to be shipped to the Moon. This means that the future of extraterrestrial construction rests on the development of technologies that are able to employ in-situ materials, such as lunar dust. Guest-Editor **Neil Leach** is a NASA Innovative Advanced Concepts Fellow, collaborating with colleagues from the University of Southern California (USC) on a research project developing a robotic fabrication technology capable of printing structures on the Moon and Mars. Here he describes the inroads that NASA and European Space Agency (ESA) consortia are independently making into 3D-printed fabrication technologies.

3D printing has begun to revolutionise all aspects of design on Earth. Much of the contents of our homes – our clothes, shoes and furniture – is now being 3D printed, and even the home itself. But what about 3D printing in Space? What impact might the technique have on the space industry? We could perhaps identify three distinct areas: the construction of space structures, fabrication of spare parts and preparation of food. In each case, 3D printing offers potential advantages. From an architectural perspective, however, the construction of structures is clearly the most significant, and one of the reasons for this is cost. It is simply too expensive to transport building materials from Earth; for example, it could cost up to $2 million to transport an ordinary brick to the Moon. Safety is another factor; the use of 3D-printed fabrication technologies would allow habitats and infrastructure to be constructed by robots ahead of human presence, reducing the risk of radiation exposure for construction workers.

Given the cost of delivering materials to space, both NASA and the European Space Agency (ESA) pursue a policy of in-situ resource utilisation (ISRU), which – in plain language – means making the most of materials available on site. In terms of printing on the Moon, the natural choice of construction material is lunar regolith, the fine, powdery, graphite-like substance that coats its surface. Likewise on Mars is Martian regolith, which is rich in iron deposits that could also be mined.[1]

Printing on the Moon poses a number of obvious problems. Firstly, the Moon is subject to an extreme range of temperatures, varying from 123⁰C (253⁰F) during the day to –233⁰C (–387⁰F) at night. Moreover, there is a significant temperature difference between stark daylight and shadow. These can cause problems in terms of curing and other construction processes. Secondly, the length of a lunar day – approximately 14 times the length of a terrestrial day – means that there will be significant periods with no sunlight, which is inconvenient if solar power is to be the primary source of energy.[2] Thirdly are other issues such as the problems of operating in a vacuum, and the challenges presented by meteorites, radiation and light intensity, which complicate matters still further. Fourthly, it is still not clear how much water – if any – exists on the Moon. And finally, any robotic system will need to be 100 per cent reliable if it is to operate without a robust maintenance support system.

There are, however, a few significant advantages to building on the Moon. The reduced gravity means that buckling forces are less, and because there is no atmosphere there is no wind or rain. The lack of wind means that there are no lateral forces to contend with, and the lack of rain means that construction does not need to be halted in inclement weather. The Moon is also a seismically quiet environment.[3] In general, though, the disadvantages of building on the Moon outweigh the advantages.

Mars poses similar problems, although in some respects conditions are closer to those on Earth. The length of a Martian day, for example, is almost the same as an earth day, and Mars – unlike the Moon – also has seasons. In addition Mars has a slight atmosphere, although it consists of 95 per cent carbon dioxide, and a gravitational force of around 38 per cent of that of the Earth, greater than that on the Moon. But conditions still remain hostile, with similar problems with radiation, and a severely cold climate where temperatures vary between 20⁰C and –153⁰C (68⁰F and –243⁰F). And, unlike the Moon, Mars suffers from dust storms and gusts of wind of up to 30 metres (100 feet) per second.

There are two rival consortia that have been sponsored to conduct research on the potential for 3D printing structures on the Moon and Mars. One is sponsored by the ESA and exploits the potential of D-Shape (a large-scale 3D printer that uses stereolithography, a layer-by-layer printing process, to bind sand with an inorganic binder to create stone-like objects) in order to print structures on the Moon. The ESA consortium is made up of engineer Enrico Dini (the inventor of D-Shape), architects Foster + Partners, space consultants Alta SpA and research scientists at the Laboratorio di Robotica Percettiva (PERCRO) of the Scuola Superiore Sant'Anna. The other is sponsored by NASA and exploits the potential of the Contour Crafting (CC) process (a layered printing technology that extrudes concrete through a

computer-controlled nozzle) to print structures on the Moon and Mars. The NASA consortium consists of mechanical engineer Behrokh Khoshnevis (the inventor of CC), myself as architect, structural engineer Anders Carlson and space architect Madhu Thangavelu, all from the University of Southern California (USC).

D-Shape

The D-Shape 3D printing technology effectively operates as a giant Z Corp printer.[4] The system was developed by Enrico Dini to increase the scale of 3D printing operations in order to print objects the size of buildings at a low cost. Dini experimented initially in the use of epoxy or polyurethane resins that were used as a form of binder and deposited into various forms of stone dust or powder. However, he soon abandoned this because of the flammability and toxicity of the resins. Moreover, the resins also required a high-maintenance nozzle, and had the added disadvantage of producing a conglomerate with a low elasticity modulus leading to deformation in the final object.

As a result, Dini began using an alternative, a 'chlorate based, low viscosity, high superficial tension liquid with extraordinary reticulate properties if added to metallic oxides used as a catalyzer'.[5] This had the added benefit of being cheap and requiring only a low-maintenance nozzle. It also sets faster and has higher-tensile properties:

> The catalyst contains metal oxides. This way, the granular material is not inert during the catalytic reaction, and instead it is actively and deeply involved in the reaction. Therefore, the material obtained through this method is not an ordinary concrete material, ie a poor tension-resistant material in which inert granules are slightly bound together; instead it is a mineral-like material, which demonstrates a high level of hardness and a high tensile strength, due to tough microcrystalline structure.[6]

The collaboration on the Moon project posits the ideas of printing habitable structures using regolith and Dini's proprietary 'ink'. The ESA proposal deploys an initial inflatable system to support the initial printing activities. This would then be removed and a secondary inflatable system inserted to provide the pressurised interior. Given that the main printed structure would struggle to contain the thrust of a pressurised internal volume, the secondary inflatable system is an absolute necessity.[7] The shell of the structure would have a honeycomb structure in order to reduce the amount of ink needed for printing yet retain its structural integrity. As a result, the outer printed shell would provide protection from radiation and meteorites, while the inner inflated membrane would provide the pressurised container for habitation.

One of the advantages of D-Shape is that it prints on a bed of regolith that serves to support whatever structure is being printed. This allows shallow arches to be printed.

One of the advantages of D-Shape is that it prints on a bed of regolith that serves to support whatever structure is being printed. This allows shallow arches to be printed. By contrast, one of the disadvantages is that its ink needs to be transported from Earth, which would be costly, despite attempts to reduce the amount of printing using honeycomb construction that maintains the effective depth of the structural system while reducing the mass involved.

However, the main disadvantage of D-Shape is that of having to inject fluids in a vacuum. Although there are also challenges with Contour Crafting, in that pumping is impossible in a vacuum, thereby necessitating an alternative method of depositing aggregate, those faced by D-Shape are more severe. The argument has been made that the fluid can embed itself quickly in the regolith, but the vacuum of the Moon will undoubtedly cause considerable problems for the D-Shape technique.

A section of walling fabricated using D-Shape printing technology reveals the honeycomb structure used to reduce the amount of 'ink' in construction.

Behrokh Khoshnevis, Neil Leach, Anders Carlson and Madhu Thangavelu (University of Southern California), Contour Crafting, 2012
right: A road is seen being printed using CC robotic fabrication technology with a shelter for a lander and a regolith processing plant in the background.

centre: A lander is seen coming in to land on a landing pad with a blast wall printed using CC robotic fabrication technology.

bottom: Contour Crafting (CC) robotic fabrication technology housed on an ATHLETE moon rover printing a parabolic unpressurised shelter for a lander.

Contour Crafting

Contour Crafting is a digitally controlled construction process invented by Professor Behrokh Khoshnevis that fabricates components directly from computer models, using layered fabrication technology by extruding concrete through a computer-guided nozzle. Importantly, the technique involves the use of a trowel that follows the nozzle and smoothes out the surface of the extruded material. The material used is a form of rapid-hardening cement that gains sufficient strength to be self-supporting almost immediately after extrusion, although it does not gain its full strength until later.

CC successfully obviates the need for any formwork or shuttering. In traditional concrete construction, not only does formwork entail a costly and time-consuming secondary process of construction, it is also often discarded after use, rendering concrete construction environmentally unsustainable. By comparison, CC is a relatively rapid, environmentally sustainable and cheap method of construction, once the initial cost of the fabrication technology has been accommodated.

CC favours a particular tectonic logic of construction based on a gravitational logic and involving slight incremental deviations from the vertical: '[CC] entails either a certain "gothic" logic of construction that, for example, relies on relatively steep vaults and avoids the use of shallow arches, or an inventive use of techniques of layering that allow a wider range of forms to be assembled. Traditional construction methods for building rounded abode vaults using bricks, for example, deploy an initial skin of brickwork whose courses are set at an angle to the base of the intended vault.'[8] Compared to D-Shape, CC is therefore less suitable for printing shallow arches. It is still possible to print shallow arches using the CC technique, although the arches would have to be printed horizontally on a flat surface and then robotically hoisted into their vertical position. CC may also require additional tensile reinforcement. This can take the form of metal ties or cleats inserted robotically into the aggregate or fibres extruded with the aggregate.

One of the key differences between the NASA and ESA proposals is that the ESA aims to create pressurised habitats for human occupation, whereas the NASA project is only for infrastructural elements, such as landing pads, roads, unpressurised shelters and blast walls. This is in line with NASA's current policy of sending ready-made habitats into space, reserving ISRU activities for

Made In Space, 3D printer, 2013
top: Made in Space has designed a 3D printer specifically for use in Space.

right: A Made in Space 3D printer is seen undergoing tests in zero-degree gravity conditions.

infrastructural elements. In the NASA-funded research project exploring the use of CC on the Moon and Mars, two techniques have been pursued. One employs a CC robot mounted on an All-Terrain Hex-Legged Extra-Terrestrial Explorer (ATHLETE) lunar rover extruding concrete through a nozzle. The other technique being explored is a form of sintering, used to create tiles with greater tolerances for landing pads and roads.

Given that there is little or no water on the Moon, the CC system relies on sulphur as a binding agent, as opposed to water, which is the traditional binder in concrete construction. Sulphur is present on the Moon, but it would still need to be mined. The whole process of mining on the Moon is challenging for a number of technical reasons, and there is also the fact that its surface is visible from any point on Earth, and care should be taken to avoid disfiguring it – unless the mining is performed on the side that is never seen from Earth.[9] Care should also be taken to ensure that the sulphur-based regolith is not exposed to extreme temperatures, given that sulphur melts at 120^{0}C (248^{0}F).

In short, both D-Shape and CC have advantages and disadvantages. It is fair to say, however, that at present both suffer from insufficient prototyping in a terrestrial context. It makes little sense to send any robotic fabrication technology to the Moon that has not been tried and tested fully on Earth, as maintenance would be a key issue. Both systems would need to be 100 per cent reliable to be deployed in an extraterrestrial context.

Other Applications in Space

3D printing offers considerable benefits in terms of spare parts. It makes more sense to be able to print spare parts on demand in Space than to bring them on board, or have them delivered by a supply ship. However, the real problem for 3D printing in Space is the lack of gravity. Given that most terrestrial 3D printing technologies depend on a bed of powder in which the object 'floats' as it is being printed, an alternative technique must be developed. One company pursuing these challenges is Made In Space, which has produced a 3D printer to be used on the International Space Station:[10] an initial prototype for 3D printing plastics is currently being deployed and a second for printing metals will follow shortly.

Prepackaged food could also be made more appealing in terms of variety, flavour, form and texture with the use of 3D printing, and NASA is currently exploring ways of 3D printing food in Space.[11] One of the key concerns with missions into deep space, such as missions to Mars, is to ensure that astronauts are able to have a healthy diet that meets their nutritional needs and contains enough variety. Given that refrigeration and freezing require significant amounts of energy, current policy is to only provide shelf-stable foods that are individually prepackaged. Technologies used for processing can also degrade micronutrients.[12] However, flights to Mars are likely to exceed the shelf life of even these pre-prepared foods, and alternative ways of preparing foods must be found. 3D printing offers the advantage of customising food production, offering variety and a range of possible ingredients. ᗡ

Notes

1. Iron deposits on Mars would prove very useful in the production of steel to be used in reinforcing any printed structure. On this see Robert Zubrin, *The Case for Mars: The Plan to Settle the Red Planet and Why We Must*, Free Press (New York), 2nd edn, 2011, Kindle edition, location 3748.
2. One way to ensure a continuous source of solar power is to locate solar panels at either pole on pylons high enough to guarantee constant exposure to sunlight.
3. Grant Heiken, David Vaniman, Bevan French and Jack Schmitt (eds), *Lunar Sourcebook: A User's Guide to the Moon*. Cambridge University Press (Cambridge), 1991.
4. Z Corporation (commonly abbreviated to Z Corp) is a rapid prototyping process that employs an inkjet-like printing head that moves across a bed of powder, selectively depositing a liquid binding material.
5. Enrico Dini, 'Printing Architecture', in Philip Yuan and Neil Leach (eds), *Fabricating the Future*, Tongji University Press (Shanghai), 2012, p 114.
6. Ibid, p 115.
7. Moreover, the traditional terrestrial technique of imposing greater load to contain the pressure would not work so well on the Moon, in that six times the amount of matter would be required to create such a thrust, given that the gravity on the Moon is one-sixth of that on Earth.
8. Neil Leach, Behrokh Khoshnevis, Madhu Thangavelu and Anders Carlson, 'Robotic Construction by Contour Crafting: The Case of Lunar Construction', *International Journal of Architectural Computing*, 10 (3), September 2012, p 423.
9. The side of the moon that is not seen from Earth is often called the 'dark side' of the moon, although in fact it receives as much sunlight as the visible side.
10. See www.madeinspace.us.
11. www.nasa.gov/directorates/spacetech/home/feature_3d_food.html#.U571VJXz3zJ.
12. www.nasa.gov/directorates/spacetech/home/feature_3d_food_prt.htm.

Sandra Häuplik-Meusburger

ASTRONAUTS ORBITING ON THEIR STOMACHS

THE NEED TO DESIGN FOR THE CONSUMPTION AND PRODUCTION OF FOOD IN SPACE

The sustainable and convivial habitation of Space requires the provision of a ready food supply that does not have to be transported from Earth. Architect and space researcher **Sandra Häuplik-Meusburger** highlights how important it is that Space Architecture fully accommodates and abets the consumption and production of food.

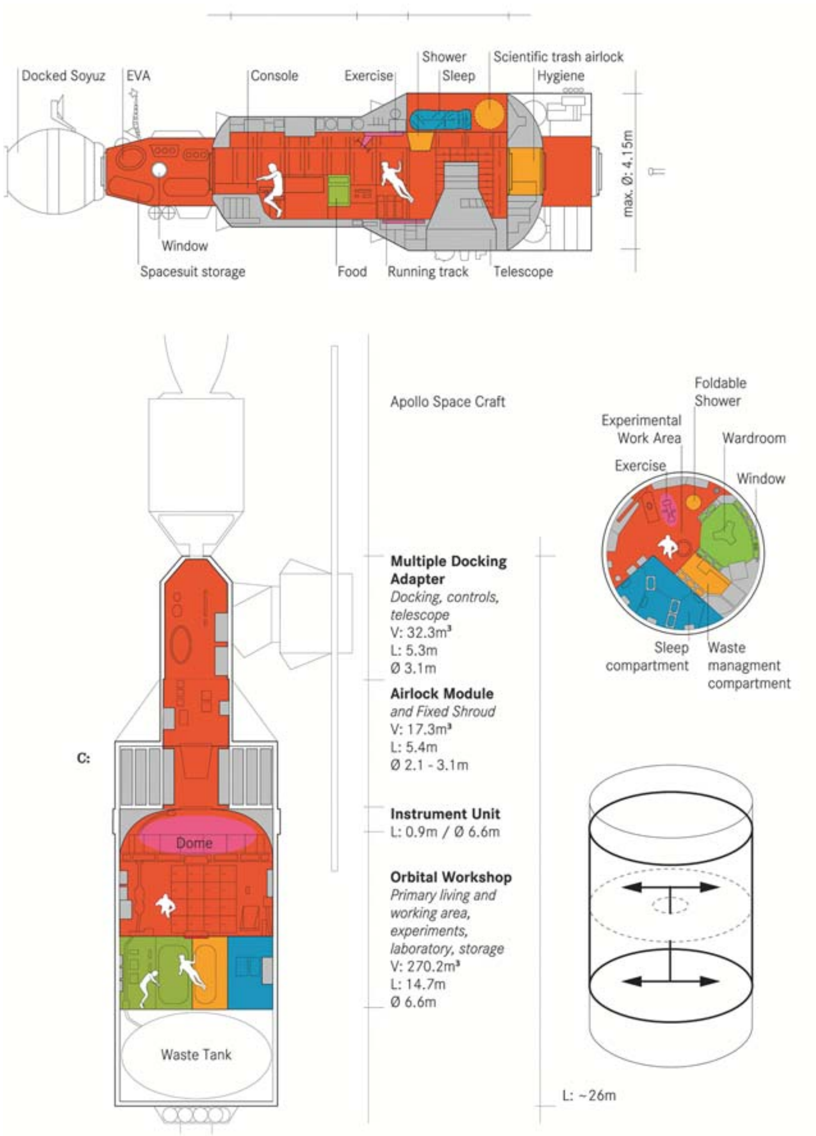
Mercury (1958–63), Gemini (1962–6) and Apollo (1967–72) astronauts ate bite-sized food and liquids in aluminium tubes, but this has changed. Today astronauts eat food prepared to fit their dietary requirements and personal preferences. It is grown, cooked and prepared for them on Earth. Even fresh food is shipped to the International Space Station. This is a luxury that researchers on Antarctica stations can currently only dream of,[1] and it is certainly not yet possible for future spacefarers off to distant places. Looking ahead, aeronautical design needs to accommodate the consumption and production of food.

Space architecture, planning and building is different to that on Earth, but the basic human requirements do not change. In an isolated, minimal and confined environment such as a space station, the design integration of human factors and habitability becomes absolutely critical. While interviewing astronauts about their daily life, it became apparent that food is one of the most important habitability topics in such an isolated space.[2] It is also a key factor for successful colonisation of Space.[3]

Food Systems and Astronauts' Experiences

Astronauts require high nutritional, well-balanced and tasty food to maintain health and to be active. Designing food systems is complex. Food must be grown, cared for, harvested and processed. It must be appealing to eat, and fast and easy to prepare and store while maintaining its quality. Ideally, it is recycled.

When listening to astronauts' experiences, the list of discomforts regarding food quality becomes long; the lack of taste in particular was an issue for many of the earlier spacefarers in the late 1960s and early 1970s, as in order not to over-stimulate the intestinal system, the food was prepared using few spices. Thus astronauts were always looking for something that had a little more taste. Harrison Schmitt's favourites were the bacon squares. Buzz Aldrin enjoyed the shrimps. Paul Weitz went for the ice cream. However, by the mid-1970s, cosmonauts and astronauts on the Russian Salyut space research stations were able to eat fresh food such as tomatoes, coriander and cucumbers from their orbital space gardens, and some even had the possibility of a sip of wine or vodka with their food. For the long-term Mir (1986–2001) citizen Jean-Pierre Haigneré, 'food was just taking medicine'. It



Sandra Häuplik-Meusburger, Architecture for Astronauts, interior layout comparison of the Salyut 6/7 and Skylab space stations, 2011
above and right: Cross-section and Plan showing the spatial allocation of the human activities: Sleep (blue), hygiene (yellow), food (green), work (red) and leisure (magenta).

Skylab 2 astronauts Joseph P Kerwin, Paul J Weitz and Charles Conrad having a meal together in the wardroom of the Skylab Orbital Workshop Trainer, 1973
opposite left: The table was designed by the industrial designer Raymond Loewy.

International Space Station Expedition 4 and STS-110 crew members share a social meal in the Zvezda Service Module, 2001
opposite right: Crew members try to fit around the table.

was uninteresting, but with a little fresh food and a bit of wine, they would occasionally prepare a special meal 'to make the life easier, more fun'.[4]

Over the last 40 years, food systems for outer space habitats have changed a great deal, and their design has become increasingly important. NASA's Apollo missions were too short and available space too small to allow dedicated areas for food preparation and eating, and the Soviet Union's Salyut stations (1971–86) were the first to be structured in zones for different activities, including a table for work and having dinner together. However, NASA's Skylab station (inhabited 1973–4) had a 14-metre (46-foot) Orbital Workshop module with a 14.5-cubic-metre (512-cubic-feet) specially designed wardroom dedicated for food preparation and dining. To date it is the largest living and working space ever constructed for a space station, with human activity areas clearly separated. At the wardroom centre table, each astronaut could heat his food individually in a futuristic-looking food tray, while looking out of a big window. The table was designed to avoid hierarchical positions through its triangular layout and to support social cohesion. It could accommodate all three crew members at the same time using a variety of microgravity restraints.[5]

The food facilities onboard the International Space Station, which was launched in 1998, include a galley with a table, a hot water dispenser and food storage. Though a 'food preparation and dining room' was planned for the US Habitation module, that module was never built. However, having meals together, in contrast to long, dull or work-loaded days, is considered an important social activity and has become a future design requirement.

Technical Greenhouses, Habitability and Human Factor Design

Food can be grown in microgravity. The pioneering Oasis greenhouse on Salyut 1 (launched in April 1971) led to the implementation of plant-growing facilities on the later Salyut stations, on Mir and on the International Space Station, and the first space-grown vegetables were reportedly eaten in 1975 onboard Salyut 4. Since 2002, the small LADA Greenhouse system (the leaf chamber is just 16 x 20 x 26 cm/6 x 8 x 10 inches) has been used onboard the International Space Station to study how plants grow in microgravity and to grow

Future greenhouse systems may include personal portable plant cultivation subsystems to improve astronauts' quality of life in these isolated environments.

edible vegetables for the astronauts. LADA includes a control module and was sent to the station already equipped with the root media for the plants to be grown and eaten in Space.[6]

The further away we travel, the more autonomous and larger greenhouses will become. They will be fundamentally different to what we are used to on Earth, or even onboard the International Space Station. Their design will depend upon factors of the environment, including different gravity conditions, microclimates, and the use of in-situ resources such as available soil and recyclable biomaterials.[7] Aside from nutritional and life support system applications, their human-related design will be equally important. Habitability-related benefits include sensory and spatial enhancement of the otherwise technical and monotonous spacecraft environment. These benefits can be provided by plants through gardening or watching them grow and change, as well as the design of their growth chambers and related interiors. Salyut cosmonauts were the first to use plants to 'mature and colour [their] life in this machine-filled hall'[8] by 'turning it into a jungle'.[9] For long-term Salyut cosmonaut Valentin Lebedev, plants became similar to pets. As a 'window to something living', an integrated greenhouse design can provide surrogate views. Future greenhouse systems may include personal portable plant cultivation subsystems to improve astronauts' quality of life in these isolated environments.

Space Cooking, Resources and Recycling

Although today's astronauts have a rich menu to choose from, it can get boring over time. Astronauts and cosmonauts have thus been inventive in creating new meals since the early Salyut days by mixing ingredients – what they call 'space cooking'. Sandra Magnus, astronaut on International Space Station Expedition 18 in 2009, has shared her space cooking experiences in her online blog.[10] Lacking microgravity cooking facilities and tools, she used everyday working tools. With duct tape, plastic bags, foil pouches and a small knife she was able to prepare her favourite meal, tortilla, in many variations.

The desire for personalised food may soon be realised with 3D printers 'that could print anything, even structures and textures'.[11] Along with functional design for microgravity kitchens and utensils for future long-term missions, we may see personalised and tasty menus from freshly grown ingredients instantly prepared onboard that can be recycled

Space-craft Architektur, Design of a mobile plant cultivation subsystem for future technical Greenhouses, 2014
opposite top: Visualisation showing an astronaut with his personal greenhouse in a space station.

International Space Station Expedition 18 flight engineer Sandra Magnus prepares a Christmas meal at the galley in the Zvezda Service Module, 2008
Space cooking onboard the International Space Station with already available tools.

and 'eaten' to enable high levels of self-sustainability. And not only in terms of food production and recycling: self-sustainability is also a prerequisite for future longer-term mission success and safety, as it will not be possible to bring enough oxygen, water or other vital volatiles, and nor can resupplies be shipped to more distant locations.

Research into bio-regenerative life-support systems that include food production and processing with the goal of eventually achieving closed-loop systems is ongoing. In 2009, astronauts onboard the International Space Station celebrated an important milestone in self-sustainability as they drank water recycled from their urine, sweat and water and condensed from exhaled air. Quoting astronaut Jean-François Clervoy, future spacecraft will be designed 'with the need [and ability] to treat anything [in an emergency] just by itself'.[12] ᗡ

Notes

1. Reference to interviews with polar research station inhabitants taken between 2012 and 2014. Excerpts can be listened to at http://cba.fro.at/series/1491.
2. See Sandra Häuplik-Meusburger, *Architecture for Astronauts: An Activity Based Approach,* Springer Praxis Books (Vienna and New York), 2011, pp 218–23. All built and inhabited spacecraft have been analysed according to the relationship between the human and the spacecraft interior based on human activities: sleep, hygiene, food, work and leisure.
3. See NASA, 'Space Human Factors and Habitability', 6 February 2013: www.nasa.gov/exploration/humanresearch/elements/research_info_element-shfh.html#.U0OLeqJ1Ovg.
4. From personal interviews with astronauts by the author and the research for her book *Architecture for Astronauts,* op cit.
5. See W David Compton and Charles D Benson, *Living and Working in Space: A History of Skylab*, United States Government Printing (Washington DC), 1983.
6. Lori Meggs, 'Growing Plants and Vegetables in a Space Garden', 15 June 2010: www.nasa.gov/mission_pages/station/research/10-074.html.
7. From Sandra Häuplik-Meusburger, 'Greenhouse Design Integration Benefits for Extended Spaceflight', *Acta Astronautica*, 68 (1–2), 2011, pp 85–90, and 'Greenhouses and Their Humanizing Synergies', *Acta Astronautica*, 96, March/April 2014, pp 138–50.
8. See Robert Zimmerman, *Leaving Earth: Space Stations, Rival Superpowers and the Quest for Interplanetary Travel*, Joseph Henry Press (Washington DC), 2003, p 143.
9. See Robert Zimmerman, 'Growing Pains: It's the One Area of Space Science in Which You Get to Eat the Experiment', *Air & Space*, September 2003: www.airspacemag.com/space/growing-pains-4148507/.
10. See www.nasa.gov/mission_pages/station/expeditions/expedition18/journal_sandra_magnus_6.html.
11. Excerpt from a radio broadcast with Kjeld van Bommel from the Netherlands Organisation for Applied Scientific Research (TNO) on their research with food printing: see http://cba.fro.at/series/1491.
12. Excerpt from the author's unpublished interview with Jean-François Clervoy, Paris, 2009.

Carrie Paterson, Greenhouses and Their Humanizing Synergies, 2014
opposite centre: Visualisation of a spatial enhancement using mini gardens in a spacecraft.

Salyut Expedition 5 cosmonaut Victor Savinykh with 'his' plants onboard Salyut 6, 1977
opposite bottom: Anecdotal evidence shows that cosmonauts and astronauts enjoy observing and handling plants.

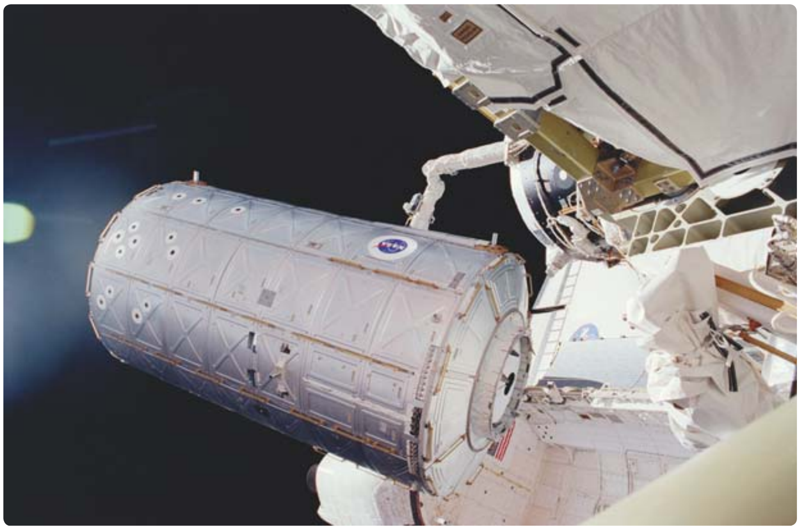
Orion Multi-Purpose Crew Vehicle (MPCV) heat shield, 2014
The Orion spacecraft being equipped with the world's largest heat shield, measuring 4.87 metres (16.5 feet) in diameter. Made from a single seamless piece of Avcoat ablator, it will be tested on Orion's first flight in December 2014 as it protects the spacecraft from temperatures reaching 2,200°C (4,000°F).

Larry Bell

Reaching Towards a New Era of Space Architecture

BRAVE NEW WORLDS

Space travel is on the brink of a new era. **Larry Bell**, Professor of Architecture and Space Architecture at the University of Houston, describes how new ambitions are being reached for, such as the exploration of distant Mars, which will require longer and ever more complex missions. At the same time Space is being opened up internationally, with the participation of China and India, and space tourism is introducing privatisation and new commercial players.



SpaceX, Dragon V2 unveiling ceremony, Hawthorne, California, 2014
The spacecraft is designed to carry people into earth orbit and was developed in partnership with NASA's Commercial Crew Program under the Commercial Crew Integrated Capability agreement.

International Space Station, NASA Destiny Laboratory, 2001
On 10 February 2001, the crews of the Space Shuttle Atlantis successfully installed the Destiny Laboratory onto the International Space Station.

Architectures in Space present new worlds of challenge and opportunity as nations join together to explore human destinations beyond Earth. This great exploration adventure began a half-century ago when a tiny orbiting capsule first carried a young Soviet cosmonaut named Yuri Gagarin around our planet on 12 April 1961. Within the next 11 years, 12 American citizens walked on the Moon as six of their crew companions orbited above.

The Russian Mir (1986–2001) and US Skylab (1973–9) space stations that soon followed demonstrated that people can live and conduct useful work under weightless conditions over prolonged periods. New generations of launch and return vehicles, including the reusable Space Shuttle that also saw service as a habitat and laboratory, made space travel routine from 1981 to 2011.

Beginning in 1998, construction of the International Space Station, the greatest collaborative enterprise and technological marvel since the dawn of mankind, has ushered in the era of a true global spacefaring community. Orbiting more than 300 kilometres (190 miles) above the Earth every 90 minutes, this epic development and assembly feat was accomplished with seamless cooperation involving professional teams from NASA, the European Space Agency (ESA), the Russian Space Agency and the Canadian Space Agency. Each government organisation, in turn, enlisted support from numerous corporate and institutional design, engineering and fabrication contractors – teams that included specially educated and experienced professionals with architectural backgrounds functioning in key roles.

Longer Missions Present Larger Architectural Challenges

As the international community extends human missions in terms of both distance and duration, the challenges to support future voyagers and settlers become ever more complex and daunting. Unlike, relatively, very short 'sprints' to the International Space Station's low earth orbit or even to the Moon and back, round-trip missions to Mars will require at least three years, with the majority of that time spent in transit under psychologically claustrophobic and physically deconditioning weightless conditions. Low gravity (one-sixth Earth gravity on the Moon, and one-third Earth gravity conditions on Mars) will add compensatory exercise requirements to retain muscular and cardiovascular health; exposures to life-threatening space radiation risks must be mitigated; intervention responses must be provided for an endless variety of equipment and medical emergencies; and satisfying nutritional and recreational requirements will be essential to sustain crew health, morale and performance under long periods of isolation, to mention but a few preparedness prerequisites.

An evolution from 'right stuff' military pilot astronauts to ISS scientific specialists to future lunar/Mars explorers or settlers will also impact planning in profound ways. Each stage imposes priorities to accommodate greater inhabitant diversity and self-reliant autonomy. This will include comprehensive planning and design for multi-cultural crew mixes, specialised and multi-tasking roles, broader long-term age- and gender-related health factors, and cohabited marriage relationships.

Space: An International Market

In addition to an evolving privatisation of 'space citizenry', emerging commercial interest is opening up new entrepreneurial space markets. Sir Richard Branson plans to offer commercial Virgin Galactic space tours. Space Exploration Technologies Corporation (SpaceX), owned by PayPal cofounder

Sasakawa International Center for Space Architecture (SICSA), Commercial Space Development Project, University of Houston, Texas, 2002

below: Laboratory module. Space offers an unlimited vacuum and 'weightless' environment for a variety of laboratory experiments and production processes.

right: A large volume and variety of replacement parts and supplies must be made immediately available to maintain all commercial on-orbit operations at mature stages of development.

Elon Musk, has already accomplished two unmanned flights to the International Space Station, and is focused upon readying a Dragon capsule to carry up to seven people. Boeing has progressed to final design stages for its CST-100 vehicle, a capsule that will fly atop a United Launch Alliance Atlas 5 rocket, and plans to launch its first International Space Station crew in 2016. Sierra Nevada's Dream Chaser features a winged vehicle design that will also fly on an Atlas 5, with a target first manned launch date in 2016 or 2017.

Las Vegas-based Bigelow Aerospace (see pp 68–9) has even more ambitious plans. The company intends to be the first to operate a commercial space hotel, and is scheduled to put an inflatable Sundancer module in orbit for operational status in 2015. The 180-cubic-metre (6,357-cubic-feet) facility is designed to accommodate up to six people for short-duration stays, and three for longer periods. Sundancer will serve as a test for a three-module commercial version that is currently under development. Bigelow has previously demonstrated two unmanned smaller-scale prototypes launched on Russian spacecraft.

China is progressing with ambitious space plans as well. The country sent its first astronaut into space in 2003, the third country after Russia and the US to achieve independent manned space travel. Then in June 2013, three Chinese astronauts spent 15 days in orbit and docked with an experimental laboratory, part of Beijing's plan to establish an operational space station by 2020.

President Xi Jinping has made it very clear he intends to have China establish itself as a space superpower. In December 2013, the Chinese launched and landed a robotic rover called Yutu (Jade Rabbit) in the northwest corner of the giant Imbrium Basin, the left eye of the 'Man in the Moon', to survey the surface. Zhao Xiaojin, director of aerospace for the China Aerospace Science and Technology Corporation, described the rover as a high-altitude 'patrolman' carrying the dreams of Asia.[1] The next stage in 2017 will likely land a lunar probe, release a moon rover and return a probe to Earth.

Yutu's lander design is far too big to have been designed for tiny rovers. Its size is larger than the one used for the NASA Apollo programme (1967–72), suggesting that it must have been engineered for the addition of a crew cabin module and return-to-orbit vehicle for lunar astronauts. The Chinese are also developing an Apollo-class moon rocket.

Russia is advancing towards several unmanned lunar landing missions, most likely in preparation for human Mars surface operations. Four of these, which will be launched between 2015 and 2020, will aim at the Moon's south pole. Their most logical goal is to explore ways to collect and process surface resources as an experimental laboratory for future human habitation on both the Moon and the Red Planet.

Not wanting to be left behind other spacefaring nations, India has dispatched an unmanned probe named Mangalyaan (Marscraft) to orbit Mars. Upon the probe's successful arrival, India's space agency becomes the fourth in the world to reach Mars following the US, Russia and Europe. Its Mangalyaan launch is broadly recognised as the first salvo in a burgeoning space race with China, Japan, South Korea and other emerging world powers. Like China, it will also include lunar rovers.

Brave New Worlds

Where and how far will our near-term international space future reach in these difficult and uncertain economic times? Given so many other urgent priorities, can we afford such costly programmes? When asked this question, Nisha Agrawal, chief executive of Oxfam in India, offered an answer during a BBC interview:

Sasakawa International Center for Space Architecture (SICSA), Minimalist mission to Mars, University of Houston, Texas, 2013
A minimalistic approach to a Mars mission using commercial space launch and habitat capabilities.

> India is home to poor people but it's also an emerging economy, it's a middle-income country, it's a member of the G20. What is hard for people to get their head around is that we are home to poverty but also a global power … We are not really one country but two in one. And we need to do both things: contribute to global knowledge as well as take care of poor people at home.[2]

K Radhakrishnan, chair of the Indian Space Research Organisation (ISRO), offered a similar reply:

> Why India has to be in the space programme is a question that has been asked over the last 50 years. The answer then, now and in the future will be: 'It is for finding solutions to the problems of man and society'.[3]

And what about American and European space futures? Having realised countless achievements and paybacks from our investments in space exploration that have driven new technological advancements, transformed our trade economies, and revolutionised global communications, it is unthinkable that progress will be allowed to stop. Just as India and China now recognise that they can and must make commitments to ensure their places in the high frontier, the US and Europe also cannot afford not to.

Sixteen years ago Neil Armstrong told BBC science correspondent Pallab Ghosh: 'The dream remains! The reality has faded a bit, but it will come back, in time.'[4] Thanks to cost-saving technology advancements, expanding entrepreneurial interest, and the successful International Space Station collaboration precedent, there is good reason to believe that time has now arrived. Accordingly, Space Architecture research and design can be expected to play important roles in making those resulting new worlds of opportunity livable and safe.

Many large questions, however, remain to be answered. How far will those journeys to new worlds take humankind? Which nations will lead, which will join, and what will they contribute? What will those spacefaring nations discover, at what costs, and who will benefit most? Finally and most importantly, in what ways will fruits of international cooperation essential for success advance progress where it matters most – to benefit all voyagers on Spaceship Earth? ⌂

Notes
1. Xinhua English News: 'China Unveils its First and Unnamed Moon Rover', 25 September 2013: http://news.xinhuanet.com/english/china/2013-09/25/c_132750241.htm.
2. BBC News, 'India's First Rocket Blasts Off to Mars', 5 November 2013: www.bbc.com/news/science-environment-24729073.
3. Ibid.
4. BBC News, Paul Rincon, 'Neil Armstrong: "Diffident" Emissary of Mankind', 26 August 2012: www.bbc.com/news/science-environment-19383607.

Neil Leach

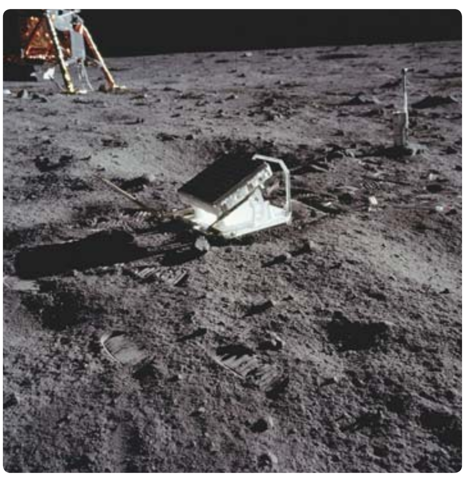
TERRES FEED..

Endeavour self-portrait, International Space Station, August 2007
The Earth reflected: A stunning image of the Earth caught in the reflection off the visor of astronaut Clay Anderson as he takes a self-portrait on extra-vehicular activity (EVA) outside the International Space Station during the shuttle orbiter Endeavour's mission to expand the station.

TRIAL BACK.

REFLECTIONS ON THE SPACE INDUSTRY

Guest-Editor **Neil Leach** contemplates the current status quo of space exploration and our attitudes towards it. Whereas in the 1960s the space industry was driven by the competitive enmity of the Cold War, how are our outlook and initiatives calibrated now by earthbound considerations? How do approaches towards Space reflect those on Earth? Has a view from Space, for instance, enabled us to recognise the preciousness of our planet as it increasingly comes under fire? What opportunities does Space afford for technological transfer from the extraterrestrial to the terrestrial?



Apollo 11 Lunar Laser Ranging Experiment, the Moon, July 1969
These retroreflectors were planted on the Moon by Buzz Aldrin and Neil Armstrong during their Apollo 11 mission. In subsequent Apollo missions, other more sophisticated arrays of mirrors were installed.

In one of their less well documented activities while on the Sea of Tranquility over 40 years ago, Buzz Aldrin and Neil Armstrong installed an array of mirrors. The purpose of these mirrors was to allow scientists to ascertain more precisely the position of the Moon in Space by 'pinging' them with lasers. In some senses, however, it could be argued that the Moon is itself already a giant mirror, along with Space in general, in that it reflects very precisely our own earthly aspirations. It becomes a surface onto which we project our ambitions, and in which we see ourselves reflected.

What, then, does our engagement with Space say about the human condition? No account of the space industry is complete without an account of what motivates it on Earth. It is, for example, commonly accepted that the Cold War (1945–9) fuelled the first successful landing on the Moon, and that the Space Race (1957–69) was motivated primarily by rivalries on Earth. Indeed, one can only speculate on the multiple internal and external factors that contributed precisely towards the famous pledge to send an astronaut to the Moon made by President JF Kennedy on 25 May 1961. One issue, however, is clear enough: the Russians had sent a cosmonaut – Yuri Gagarin – into Space first, and for Americans to restore pride they needed to be the first to send a human being to the Moon. According to NASA:

> In general, Kennedy felt great pressure to have the United States 'catch up to and overtake' the Soviet Union in the 'space race.' Four years after the Sputnik shock of 1957, the cosmonaut Yuri Gagarin had become the first human in space on April 12, 1961, greatly embarrassing the U.S. While Alan Shepard became the first American in space on May 5, he only flew on a short suborbital flight instead of orbiting the Earth, as Gagarin had done. In addition, the Bay of Pigs fiasco in mid-April put unquantifiable pressure on Kennedy. He wanted to announce a program that the U.S. had a strong chance at achieving before the Soviet Union. After consulting with Vice President Johnson, NASA Administrator James Webb, and other officials, he concluded that landing an American on the Moon would be a very challenging technological feat, but an area of space exploration in which the U.S. actually had a potential lead. Thus the cold war is the primary contextual lens through which many historians now view Kennedy's speech.[1]

Attitudes towards Space itself seem to reflect attitudes on Earth. During the Cold War, Space was seen as a potential sanctuary. As the arms race built up, and potential crisis situations such as the Suez Crisis (1956) and Bay of Pigs Invasion (1961) threatened to trigger a conflict between nations possessing nuclear weapons, so Space appeared to some as a place to escape from the inevitability of a nuclear holocaust.[2] It is ironic, perhaps, that we have now begun to recognise that Space is certainly no safe haven. Not only is radiation in Space potentially as damaging as any radiation on Earth, but from observations on the wellbeing of astronauts and cosmonauts on the International Space Station it is clear that the lack of gravity

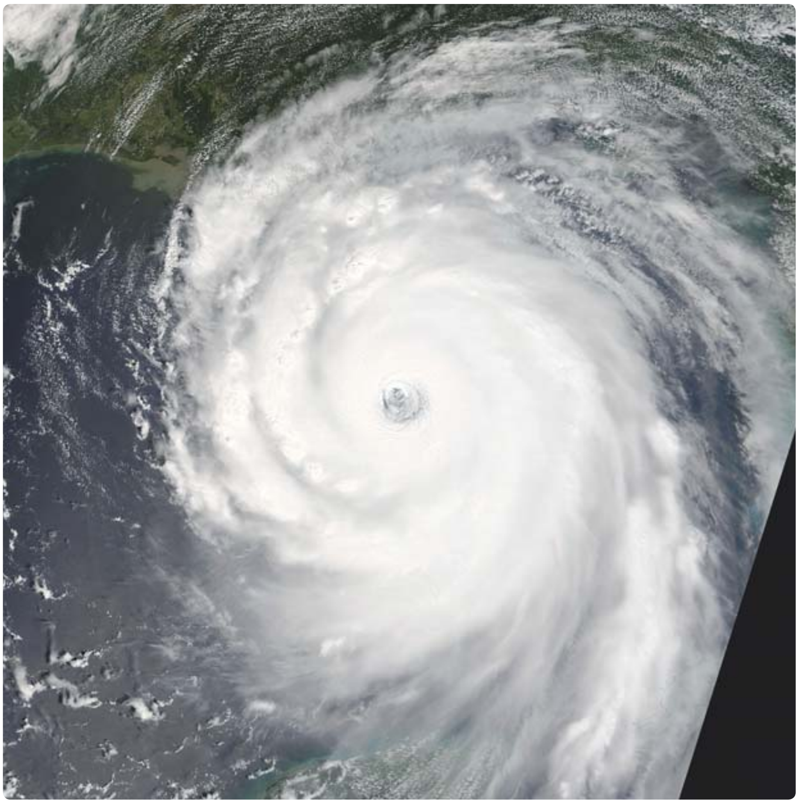
NASA Moderate Resolution Imaging Spectroradiometer (MODIS) image of Hurricane Katrina, 28 August 2005
bottom: This image of one of the most powerful storms to strike the US was taken by NASA's MODIS two hours after the National Hurricane Center issued a warning about the potential intensity of the developing hurricane.

NASA, The Blue Marble, 2002
right: This spectacular 'blue marble' view of the Earth is in fact stitched together from smaller images after months of observation. Most of the information comes from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) flying 700 kilometres (430 miles) above the Earth onboard the Terra satellite.

can have a highly detrimental impact on the human body. Similarly, economic and political attitudes reflect changes on Earth as the space industry has shifted increasingly from nation-based space organisations such as NASA to private enterprises such as Space Exploration Technologies Corporation (SpaceX). Likewise, the goals and ambitions have also shifted, with less emphasis on heroic achievements such as landing on Mars or pioneering attempts to create a two-planet culture, and more emphasis on emerging domestic concerns such as space tourism or energy farming.

Indeed, one of the surprising outcomes of the Space Race has been the realisation that the Earth itself is extremely beautiful. Apparently one of the favourite activities of astronauts/cosmonauts onboard the International Space Station is to gaze back at the Earth. Likewise, the very fragility of the Earth became apparent when viewed from Space. As Andreas Vogler comments: 'The first images from the Earth seen from space, especially as the "blue marble" taken by the 1968 circumlunar Apollo 8 team, showed us the preciousness of this blue planet with its thin atmosphere in the vast dark vacuum of space.'[3] Natural disasters, such as Hurricane Katrina, can be observed from Space, and so too volcanic explosions and the clouds of debris that they cast into the atmosphere. Moreover, Space itself is threatening to become a junkyard of disused space debris. As such, we might surmise that it is as though we human beings need to go to Space in order to recognise fully the preciousness of our own planet.

ATTITUDES TOWARDS SPACE ITSELF SEEM TO REFLECT ATTITUDES ON EARTH. DURING THE COLD WAR, SPACE WAS SEEN AS A POTENTIAL SANCTUARY.



International Space Station view of the Sarychev volcano eruption, Matua Island, Kuril Islands, Russia, 12 June 2009
Photograph of the eruption taken by astronauts orbiting the International Space Station.

Technology Transfer

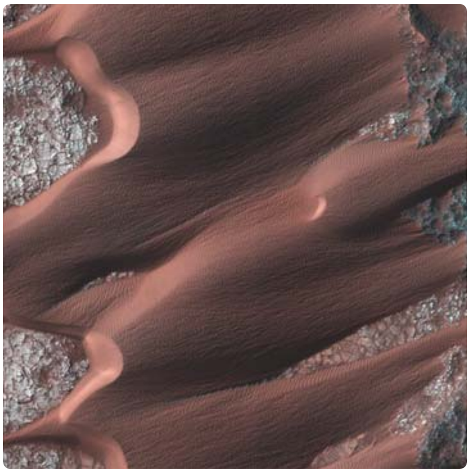
If Space, then, operates as a form of mirror to human aspirations, is there no reciprocal feedback? If our thinking about Space is informed by our operations on Earth, can operations on Earth not also be informed by our thinking about Space? In other words, what are the potential advantages from the transfer of technological developments in the space industry to our operations on Earth? NASA terms these advantages 'spinoffs':

> A spinoff is a technology originally developed to meet NASA mission needs, that has been transferred to the public, and now provides benefits for the Nation and world as a commercial product or service. NASA spinoffs enhance many aspects of daily life, including health and medicine, transportation, public safety, consumer goods, energy and environment, information technology and industrial productivity.[4]

The popular perception of Teflon – used in heat shields, space suits and cargo-hold liners – as a NASA spinoff is in fact erroneous, as is the case for both Tang and Velcro.[5] However, memory foam, freeze-dried food, 'space blankets', Dustbusters, cochlear implants and Speedo's LZR Racer swimsuits are all genuine NASA spinoffs.[6] NASA claims to have published nearly 1,800 such spinoffs. More recent developments include the use of technology developed to take high-resolution images of Mars to connect sports teams with fans, and for sensors that enable plants to send text messages to farmers when they need more water.[7]

What, then, might be the potential benefits of the space industry for the building industry? While there are may examples of individual products developed as spinoff technologies for the building industry, there are a few examples that really stand out. One is the use in tensile roofs of Teflon-coated fibreglass fabric, originally developed to provide a noncombustible material for spacesuits;[8] another is the development of photocatalytic self-cleansing surfaces;[9] and yet another is an insulating paint developed initially to protect spacecraft, but now applied to buildings.[10]

It is, however, the very constraints of Space that can offer architecture its most important message. Architecture is always born of constraints. As such, the tighter the constraints, the more exacting should be the design – and, for sure, Space Architecture is faced with very exacting constraints. Here we might talk not only about the physical limitations in terms of habitable space in space habitats (there are numerous psychological insights to be observed about the impact of living in such close quarters with other human beings in the International Space Station and other potential living accommodation in Space) and the need to optimise its use. One might also muse about the knowledge to be gained from Space in developing flexible, adaptive systems, such that while, as Constance Adams (pp 70–77) has pointed out, the International Space Station was based on principles of the International Style of architecture, so too insights on adaptability and modularity might themselves feed back into architectural culture. However, it is more likely perhaps that the most important lessons to be learnt from Space relate to sustainability and self-sufficiency.



Nili Patera sand dune, Mars, March 2014
The Nili Patera sand dune is one of the most active on Mars, and is constantly changing under the effect of the Martian winds. It is continuously monitored with the HiRISE (High Resolution Imaging Science Experiment) camera aboard NASA's Mars Reconnaissance Orbiter, with a new image acquired about every six weeks.

International Space Station view of Moscow at night, March 2012
Photo taken by a member of the Expedition 30 crew showing a solar array panel of the International Space Station on the left, and in the distance to the right the aurora borealis.

Waste needs to be kept to a minimum.[11] Marc M Cohen's Water Walls project (pp 80–81) offers an example of how waste fluids can be used to provide protection from radiation, but ideally any space habitat should be able to recycle all waste products. As such, proposals have been made to ensure a continuous, contained system whereby all waste products feed into the system itself. Tilapia fish are therefore recommended as one ideal food source, in that human beings can feed off the tilapia, which itself can feed off both human waste and various forms of vegetation, which are themselves sustained by human waste products, thus establishing a continuous feedback loop.[12] Space offers us clear lessons in terms of the efficient recycling of resources.

In the context of the building industry itself, a further lesson might be learnt from the various examples of attempts to use 3D printing in Space. NASA's policy of in-situ resource utilisation (ISRU) may itself have emerged from observations of the use of local building materials on Earth, but there is a potential feedback loop when we consider the experience to be gained for the construction industry on Earth from building experiences in Space. Water is often regarded as a relatively abundant material that can ordinarily be used without undue concern for wastage. However, in certain areas of the world, water is in short supply – most notably in areas of extreme aridity such as deserts, or even in relatively temperate zones such as Western Australia where water resources are limited. An obvious development in such areas might be gleaned from the use of sulphur-based concrete being explored by Behrokh Khoshnevis and his team (pp 112–13) as an alternative to water-based concrete, and also from the potential of sintering as a construction process in areas of high solar exposure. Equally, the use of regolith as a potential building material on the Moon and Mars suggests the use of sand as a potential ISRU building material in desert terrains using similar 3D printing processes.

In short, while it might be foolish to attempt to justify the funding expended on space programmes in terms of direct returns through spinoff technologies, there are obvious side benefits that might be accrued with respect to technological advances. Just as earthly aspirations are often reflected in our ambitions in Space, so innovations intended for Space may potentially feed their way back to ambitions on Earth. ⌂

Notes

1. See http://history.nasa.gov/moondec.html.
2. See William Sim Bainbridge, *Goals in Space: American Values and the Future of Technology*, SUNY Press (New York), 1991, p 188.
3. Andreas Vogler, 'The Universal House: An Outlook to Space-Age Housing', in Mick Eekhout (ed), *Concept House: Towards Customised Industrial Housing*, Delft University of Technology (Delft), 2005, p 77.
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9. http://spinoff.nasa.gov/Spinoff2012/ee_5.html.
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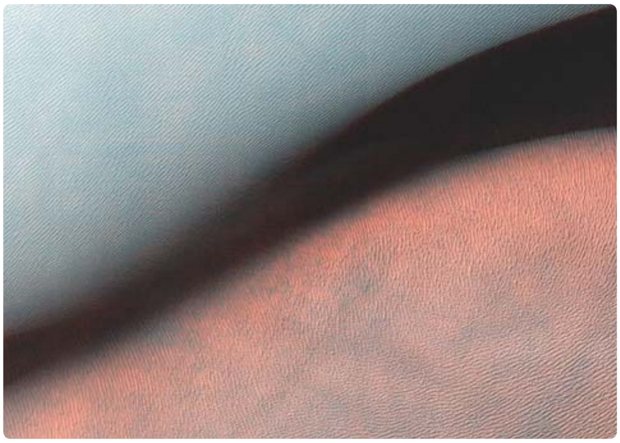
11. On this see NASA's Beyond Waste initiative: http://open.nasa.gov/blog/2012/07/16/beyondwaste/.
12. See Pam Easton, 'What's on the Menu for Future Space Feasts', NBCNews.com, 23 November 2005: http://www.nbcnews.com/id/10179202/ns/technology_and_science-space/t/whats-menu-future-space-feasts/#.U6rmtpXz3zl.



Giant landform, Juventae Chasma, Mars, 4 June 2014
Sand dunes are to be found all over Mars. The largest is called a 'draa'. This draa has a wavelength of over a kilometre, and probably took several thousands of Martian years to form.

Rachel Armstrong

SPACE IS AN FOR LIVING

COUNTERPOINT 06/2014 Nº 232 AD

Current space exploration can be viewed as an augmentation of the activities of the 20th century, albeit with a greater emphasis on new technologies and privatisation. With the continuation of this trend, could outer space be in danger of becoming a vast territory exposed to the voracity of would-be prospectors, manned by robots? **Rachel Armstrong**, Professor of Experimental Architecture at Newcastle University and guest-editor of the April 2000 AD *Space Architecture* issue, advocates a much more far-reaching biological definition of Space, driven by a concern for the natural environment, that emphasises its potential as an ecology for living in.

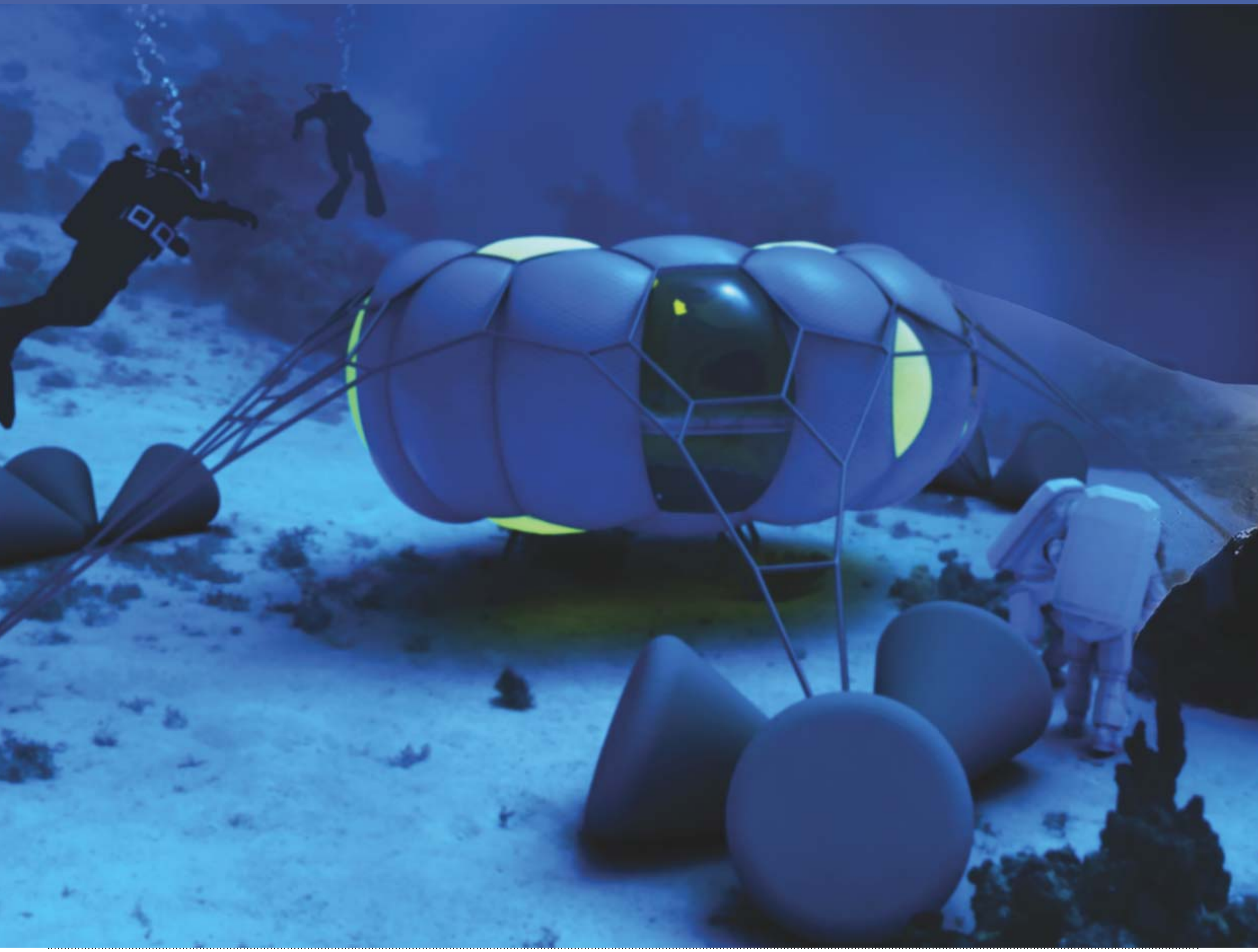
Teodor Petrov, Dark Matter, University of Central Lancashire, 2014
The drawing represents the structure of the unseen universe – an entanglement of dark matter and energy whose significance for human habitation and the production of architecture is entirely unknown.

ECOLOGY IN

Since the last edition of *Space Architecture*, which I guest edited in 2000,[1] when space tourism was just an emerging possibility, the notion of the general public going into Space has now become reality. Private individuals (namely Anousheh Ansari, Dennis Tito, Mark Shuttleworth, Richard Garriott, Guy Laliberté and Charles Simonyi) have stayed on the International Space Station after going up in the Soviet-designed Soyuz, and the first private cargo mission to the station for NASA was successfully completed by Elon Musk's Space Exploration Technologies Corporation (SpaceX), whose next step is to fly up to seven people per year to Space in a cone-shaped capsule called Dragon, starting from 2015. Further developments for a booming space tourism industry are promised by Richard Branson's Virgin Galactic, which is reaching its final stages of development. Around 700 people including businessmen, Hollywood stars and Branson's own family members have already signed up to become space tourists. And if the prospect of Space in your living room still seemed limited to the super-rich, in 2013 Canadian astronaut Chris Hadfield broke new ground in making living in Space publicly accessible through his video diaries aboard the International Space Station, which he posted through social media such as Twitter.

Indeed, living beyond Earth's domain is becoming even more attractive than ever for tourists with Bigelow Aerospace, who launched the Genesis I mission in 2006 and Genesis II in 2007, prototyping new inflatable habitats, or 'space hotels'. There are also ongoing discussions about America making a return to the Moon to exploit mineral rewards, which promise to be the building blocks of a space economy. Foster + Partners, working with the European Space Agency (ESA), is responding to this possibility by creating a process for developing lunar bases. The system uses giant 3D printers to spray scaffolding made of modular tubes and an inflatable dome with regolith. These dwellings propose to house four people and offer protection from meteorites, gamma radiation and high-temperature fluctuations.

Google and NASA are venturing even further into interplanetary space by proposing to set up systems for mining the treasures of asteroids. Yet, space exploration has also reached a tipping point in boldness, with private corporations leading the race with brave new visions such as the Mars One mission founded by Bas Lansdorp and Arno Wielders in 2011. Lansdorp and Wielders's goal is a successful unmanned mission in



2018 with a view to subsequently sending crews of four to establish a permanent human settlement on Mars from 2024. Not to be outdone in the art of visionary space enterprise, SpaceX is aiming to establish commercial missions to Mars in 2025 by seizing service provision opportunities in the areas of communications infrastructure and cargo supplies for national space agencies making forays to the Red Planet. Indeed, SpaceX's CEO and chief designer, Elon Musk, has also publicly declared his ultimate goal – to be buried there.

The Age of Modern Space Exploration

However, these bold pioneers are largely treating 21st-century Space as a continuation of the 20th century. In other words, as an extension of the American frontier and a vast terrain for prospectors and colonists.[2]

This very modern view of space exploration replays the tape of the global Industrial Revolution, which includes establishing territorial boundaries, enclosures, mechanisation and scarcity economics, albeit using the most advanced technologies of our time. Indeed, the advent of robotic space exploration is rendering human exploration within interplanetary space almost an irrelevance. Robots are more suited to the extraterrestrial environment: being hardier than we are, they last longer and pose fewer ethical issues. So while entrepreneurs are playing a personal role in pushing back the boundaries of space exploration, in the longer term robotic missions are likely to be the mainstay of national space agency endeavours – with human exploration perhaps regarded as little more than an extreme sport for the super-adventurous, super-wealthy.

An Ecological View of Space Colonisation

A modern vision for Space involving energy, materials, manufacturing and robotics – albeit being performed in a more collaborative, distributed manner and with new, portable technologies – does not speak to the 21st-century concerns of an ecologically minded global culture. As Neil Leach observes in his Introduction to this issue, Space '[is] … a mirror that reflects human concerns on Earth' (see p 15). Indeed, our first steps into Space inspired the 1970s environmental movement, with Carl Sagan's 'Pale Blue Dot', a haunting image[3] of the uniqueness of our watery planet, becoming an icon of the Space Age. In keeping with the side effects of industrial practices, space junk is already piling up in near-earth orbit and posing a risk to operational satellites and manned space vehicles.

LIQUIFIER, Compagnie Maritime d'Expertises and the University of Delft, MEDUSA subsea habitat, 2012
MEDUSA is an inflatable habitat that can be tested in a reduced-gravity underwater environment that integrates a range of proof-of-concept life-supporting elements and robot-command modules.

Since interplanetary space and the realms beyond are not a continuum of terrestrial plains, the modes for establishing our presence in alien environments are still being explored. In fact, Space has amazing properties, such as 'dark matter' – a hypothetical substance first proposed by Dutch astronomer Jan Oort in 1932 as a way of accounting for 'missing mass' in the universe – many of which are just beginning to be understood.

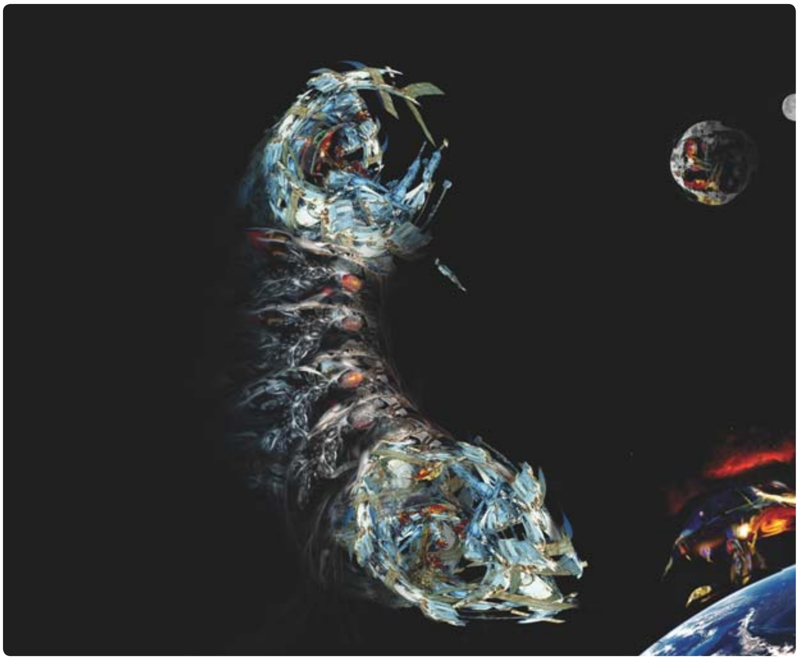
Such mysteries inspire the architectural imagination, including Project Persephone. This is a real project within the Icarus Interstellar group's portfolio that aims to catalyse the construction of the living interior of a starship within earth orbit within 100 years. It is a platform for generating technical solutions for the next wave of human expansion as well as provoking a better future for humankind beyond our planetary surface.

Ecosystems in Space

Since we are dependent on our native systems for survival, we will have to bring our environment with us when we leave Earth's orbit. This intimate entanglement with terrestrial systems confers us with a codependency and state of existence that Bruno Latour calls 'Earthbound'.[4] However, with no established ecosystems on the Moon or Mars, the challenge of interplanetary space is how we may turn these barren expanses into livable spaces. This issue of AD offers us glimpses of what an ecosystem in Space might be, such as Sandra Häuplik-Meusburger's speculative greenhouse that grows food and enhances the psychological welfare of colonists (see pp 114–17), and Marc M Cohen's closed Water Walls ecology, which recycles waste fluids and acts as a radiation shield (pp 80–81). Yet if we are to genuinely survive as settlers beyond the Earth's surface we need to invest more in these kinds of experiments and prototypes, as does 'aquabatics' pioneer Sarah Jane Pell, who is exploring an adaptive aquatic approach to the future of space colonisation through performance work, where she uses the principles of neutral buoyancy to explore how it might be to experience embodied microgravity.

Additionally, the MEDUSA project, which is a self-funded, collaborative project of international partners (the LIQUIFER Systems Group of Austria, Compagnie Maritime d'Expertises of France, and the University of Delft in the Netherlands), tests critical elements in the design and use of future inflatable habitats for the Moon, Mars or in orbit. MEDUSA can also be tested in a reduced-gravity underwater environment that integrates a range of proof-of-concept

Jon Morris and Phil Watson, World Orbit, Project Persephone, 2014
This drawing depicts the initial phases of construction of Persephone, which is assembled using space junk to produce a caddis fly shell-like rigid body that is then seeded with a soft interior fabric of artificial soils.



Jon Morris and Phil Watson, Synthetic Soil, Project Persephone, 2014
This synthetic soil fabric serves as an interface for metabolic exchanges that shape the materiality and performance of an environment. Soils promote life by preventing the participating substances from collectively reaching thermodynamic equilibrium.

elements such as interior living spaces, life-support systems and an algae greenhouse. It aims to examine the possibility of future inflatable habitats as mini 'biomes' – self-contained environmental systems – for space colonisation.

Life-Promoting Infrastructures

Our longer-term capacity to thrive in Space depends not only on the initial construction of closed living quarters, but also on how the infrastructures of life are propagated throughout interplanetary and cosmic space. In other words, architecture must be concerned not just with sealed habitats and closed ecosystems, but also with the processes of 'ecopoiesis' – the transformation of barren, non-dynamic planetary surfaces such as Mars into primitive elemental cycles that generate planetary-scale systems of exchange. These basic conditions may include the production of synthetic soils as dynamic fabrics that create the possibility of terraforming, whereby existing conditions may be shaped in ways that make them more similar to the terrestrial conditions that nourish the Earthbound. Yet, the 1967 Outer Space Treaty is hostile to these ideas and regards life either as something that needs conservation and protection, or as a contaminant. Indeed, the robustness, negotiation and complex relationships between dynamic agents that are needed to produce ecosystems through processes such as the establishment of soils are in principle hampered by these imperial agreements that work counter to an ecosystems approach to interplanetary exploration and settlement – and reassert the industrial divide between human and nature. Unless we are able to design sustainable environments that do not just focus on resource conservation, but actually promote life,[5] our chances of supporting interplanetary colonies are extremely slim, and there is currently insufficient attention being paid to its importance.

Transition to a Space-Faring Culture

The interplanetary and interstellar expansion of the human race will be most successful if achieved biologically, planet by planet, out into the Kuiper belt and the Oort cloud. Perhaps our design tactics may be similar to Freeman Dyson's Astrochicken, a thought experiment that explored the life-promoting potential of a combination of organic and electronic components, or his genetically engineered Dyson trees.[6] However, this is not the clinically clean, sanitised NASA vision of Space, but more anarchic, like life itself, and

Sarah Jane Pell, *Omnes Sumus Pulvere Stellarum*, 2014
Professional diver and 'aquabatics' performance artist Sarah Jane Pell uses techniques from the arts, media and human performance communication to explore the impact of microgravity on the human body in preparation for life in extreme environments such as extraterrestrial locations. Video still by Paolo Nespoli.

Teodor Petrov, Gravity suit, University of Central Lancashire, 2014
A future human in an alien setting, where colonists are expanding life-promoting infrastructures into the environment.

from an ecological perspective, if it is possible to initiate ecopoiesis in these environments, perhaps starting first within biospheres, they are more likely to be self-sustaining.

Consequently, space exploration needs to develop more research into architectural materials, technologies and structures that generate enlivened environments. This requires a new portfolio of technologies with lifelike properties, such as protocells, which are simple chemistries with lifelike characteristics that can move around an environment, sense it and even build microstructures.[7] It is also essential to take the lessons of terrestrial sealed environments to the next stage with us – like Biosphere 2, which taught us that we are unable to build a wholly sustainable ecosystem, even on a life-bearing planet.[8] Potentially, then, a Biosphere 3 project could develop the infrastructures that support us by titrating bio-complexity to ongoing challenges of environmental liveliness. For example, soil construction in lifeless environments could promote environmental fertility – both on Earth and beyond it – by enabling simple microbial ecosystems to thrive.[9] Perhaps the next wave of space exploration will establish living highways throughout interplanetary – and even interstellar – space, rather than simply transgressing its vast frontiers in an exploitative manner. AD

Notes
1. Rachel Armstrong (ed), AD *Space Architecture*, March/April (no 2), 2000.
2. Marina Benjamin, *Rocket Dreams: How the Space Age Shaped Our Vision of a World Beyond*, Free Press (New York), 2004.
3. 'Pale Blue Dot' was a photograph taken in 1990 by the Voyager 1 space probe. It inspired the main title of American astronomer Carl Sagan's 1994 book *Pale Blue Dot: A Vision of the Human Future in Space*, in which he combines philosophy with our knowledge of the solar system to paint a new vision of humanity.
4. Bruno Latour, 'Once Out of Nature: Natural Religion as a Pleonasm', Gifford Lecture Series, University of Edinburgh, 2013: www.youtube.com/watch?v=MC3E6vdQEzk.
5. Rachel Armstrong, 'Is There Something Beyond "Outside of the Box"?', in Terri Peters (ed), AD *Experimental Green Strategies: Redefining Ecological Design Research*, Nov/Dec (no 6), 2011, pp 130–3.
6. Freeman Dyson, *Disturbing the Universe*, Basic Books (New York), 1979.
7. Rachel Armstrong and Neil Spiller (eds), AD *Protocell Architecture*, March/April (no 2), 2011.
8. John L Allen and Anthony Blake, *Biosphere 2: The Human Experiment*, Viking (New York), 1991.
9. Rachel Armstrong, 'The Post-Epistemological Details of Oceanic Ontologies', in Mark Garcia (ed), AD *Future Details of Architecture*, July/August (no 4), 2014, pp 112–17.

Constance Adams is a specialist in high-performance architecture, particularly in architectures for human space flight at NASA and as president of Synthesis International. She shares the design copyright on the first human-rated inflatable spacecraft and has received several NASA awards for technological innovation. National Geographic honoured her as an 'Emerging Explorer' in 2005 for her work in space and terrestrial architecture and the adaptive transfer of sustainable technologies. A senior member of the American Institute of Aeronautics and Astronautics (AIAA), she holds degrees from Harvard/Radcliffe College and Yale University.

Rachel Armstrong is Professor of Experimental Architecture at the Department of Architecture, Planning and Landscape, University of Newcastle. She is Project Leader for Persephone, which is part of the Icarus Interstellar group's work to construct a starship within 100 years, and Director of Sustainability and Development for the Institute for Interstellar Studies. She is also a 2010 Senior TED Fellow, and is establishing an alternative approach to sustainability that couples with the computational properties of the natural world to develop a 21st-century production platform for the built environment, which she calls 'living' architecture,She was the guest-editor of *AD Space Architecture* in 2000, and (with Neil Spiller) of *AD Protocell Architecture* in 2011.

Larry Bell is a professor of architecture and endowed professor of Space Architecture at the University of Houston, where he founded and directs the Sasakawa International Center for Space Architecture (SICSA) and heads the world's only MS Space Architecture programme. His work with SICSA has appeared in numerous major international print and television media features including History Channel and Discovery Channel productions.

Marc M Cohen is a licensed architect who has devoted his career to developing the field of Space Architecture. He began at the NASA Ames Research Center working on wind tunnels, life science labs and aircraft support buildings before joining the Space Station programme. He also worked on humans-to-Mars studies. After 26 years he took very early retirement from NASA. Next he worked for Northrop Grumman Aerospace Systems in Los Angeles, primarily on the Altair lunar lander. In 2010 he started Marc M Cohen Architect PC, trading as Astrotecture™.

Ondřej Doule is a chair of the Space Architecture Technical Committee at the AIAA. His background is in architecture in extreme environments and space management. His research focuses on human – system integration in spaceship cockpits and space station interiors, and the application of Space Architecture principles in terrestrial architecture. His interests are also in the area of development of design standards for human spaceflight.

Sandra Häuplik-Meusburger is an architect and researcher specialising in habitability design solutions for extreme environments. She is currently teaching at the Vienna University of Technology where she leads the Emerging Fields in Architecture module. She is chairing the Habitability and Human Factors SC of the AIAA Space Architecture Technical Committee, and has worked on several aerospace design projects. She has published several scientific papers and is author of *Architecture for Astronauts* (Springer, 2011).

A Scott Howe is a licensed architect and robotics engineer at NASA's Jet Propulsion Laboratory, California Institute of Technology. He earned PhDs in architecture from the University of Michigan, and in industrial and manufacturing systems engineering from Hong Kong University. He spent 13 years in architectural practice in Tokyo, and taught for six years at Hong Kong University. He specialises in robotic construction and is currently on the NASA development team building long-duration human habitats for deep space and permanent outposts for the Moon and Mars.

Together with Brent Sherwood, he edited the seminal book *Out of This World: The New Field of Space Architecture* (AIAA, 2009).

Rod Jones graduated from Virginia Polytechnic Institute with a Bachelor of Architecture in 1984. He joined NASA to define architectural requirements for human space flight and develop architectural designs for the International Space Station. He currently leads the International Space Station Research Integration Office.

Greg Lynn has won a Golden Lion at the Venice Biennale of Architecture, received the American Academy of Arts & Letters Architecture Award, and was awarded a fellowship from United States Artists. *Time* magazine named him one of 100 of the most innovative people in the world for the 21st century, and *Forbes* magazine named him one of the 10 most influential living architects. He graduated from Miami University of Ohio with Bachelor of Environmental Design and Bachelor of Philosophy degrees, and from Princeton University with a Master of Architecture degree. He is the author of seven books.

Brent Sherwood is a space architect with 25 years of professional experience in the space industry. At Boeing, he led teams in concept engineering for human planetary exploration, space station manufacturing engineering, and commercial and space science programme development. Now at the Jet Propulsion Laboratory, he is Program Manager for solar system science mission formulation. He received a BA from Yale College, a Master of Architecture from the Yale School of Architecture, and an MS in aerospace engineering at the University of Maryland. He has published and presented over 45 papers on the exploration, development and settlement of Space.

Madhu Thangavelu conducts the ASTE527 graduate Space Exploration Architectures Concept Synthesis Studio in the Department of Astronautical Engineering within the Viterbi School of Engineering at the University of Southern California (USC), where he is also a graduate thesis adviser in the School of Architecture. He holds degrees in both engineering and architecture, and has contributed extensively to concepts in Space Architecture, especially dealing with extraterrestrial development. He is the author or co-author of over 50 technical papers on Space Architecture, lunar base design and human factors. He is co-author of the book *The Moon: Resources, Future Development and Settlement* (John Wiley & Sons, 1999), and also author of the chapter 'Living on the Moon' in the major reference work *Encyclopedia of Aerospace Engineering* (John Wiley & Sons, 2010). He is a former AIAA officer, having served as Vice Chair for Education in the Los Angeles section.

Andreas Vogler is based in Munich. He is the co-founder of Architecture and Vision, and currently director of Andreas Vogler Architect, BDA. He graduated at the Swiss Federal Institute of Technology in Zurich, and worked with Richard Horden in London, and at the Technical University of Munich. He has written numerous papers on Space Architecture prefabrication and technology transfer. His work combines aerospace, architecture, art and aid and is exhibited and published worldwide.

Robert Zubrin, an astronautical engineer, is President of the Mars Society and President of Pioneer Astronautics, an aerospace R&D company located in Lakewood, Colorado. He is also the author of *The Case for Mars: The Plan to Settle the Red Planet and Why We Must* (Simon & Schuster, 1996).

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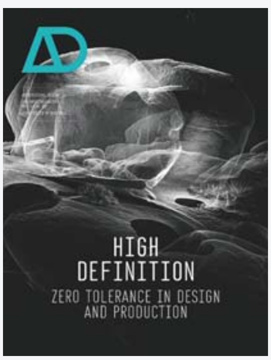

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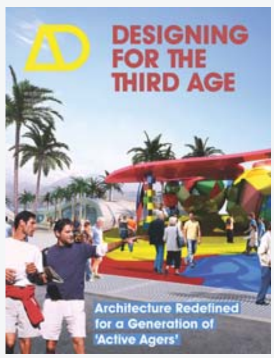

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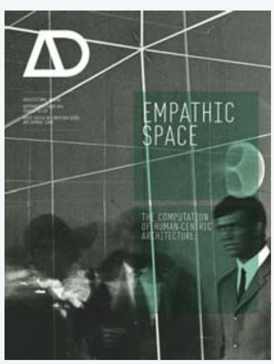

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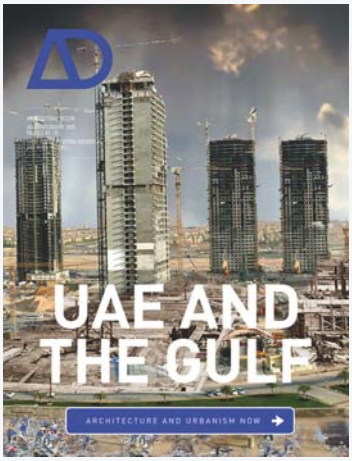

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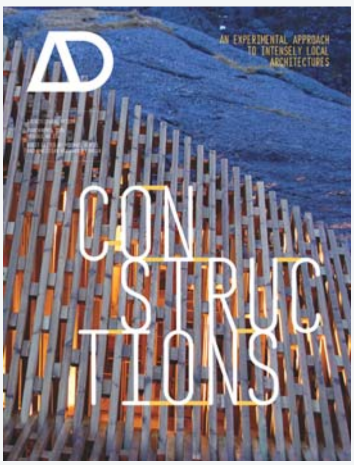
JANUARY/FEBRUARY 2015 – PROFILE NO 233
UAE AND THE GULF: ARCHITECTURE AND URBANISM NOW
GUEST-EDITED BY GEORGE KATODRYTIS AND KEVIN MITCHELL

At the end of the 20th century, Dubai attracted international media attention as the world sought to make sense of the city's extraordinary growth. Exuberant projects such as the Burj Al Arab, the Burj Khalifa and the Palm Islands attracted investment in dreams to transform the region. While the global financial crisis kept dreams from becoming reality, this issue of AD seeks to present a view of architecture and urbanism in the United Arab Emirates (UAE) and other states in the wider Gulf Cooperation Council (GCC) at a time when greater economic stability promises new beginnings. It features examples of architecture that transcend the preoccupation with fabricating images, and traces the process of making contemporary Gulf cities, from material tectonics to large-scale masterplans. By presenting the architecture of UAE and the Gulf within the context of broader regional developments and global trends, it highlights how projects in the GCC have contributed to unprecedented urban growth, while emphasising the continuing environmental challenges of building in the region. In addition to highlighting various sustainable initiatives intended to counteract these challenges, the issue also explores how computational design and new technologies are being innovatively employed to mitigate the impact of arid climates.

Contributors: Ameena Ahmadi, Noura Al Sayeh, Terri Boake, Robert Cooke, Adam Himes, Mona El Mousfy, Kelly Hutzell, Varkki Pallathucheril, Todd Reisz, Rami el Samahy, Sharmeen Syed, Steven Velegrinis, Sarina Wakefield, Jeffrey Willis.
International architects: Allies and Morrison, Foster + Partners, Frank Gehry, HOK, IM Pei, Rem Koolhaas, Legoretta+Legoretta, Jean Nouvel, Perkins + Will, SOM.
Regional architects: AGi Architects (Kuwait), dxb.lab (UAE), X Architects (UAE), SHAPE Architecture Practice + Research (UAE).



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MARCH/APRIL 2015 – PROFILE NO 234
CONSTRUCTIONS: AN EXPERIMENTAL APPROACH TO INTENSELY LOCAL ARCHITECTURES
GUEST-EDITED BY MICHAEL HENSEL AND CHRISTIAN HERMANSEN CORDUA

The current trend for constructing experimental structures is now an international phenomenon. It has been taken up worldwide by design professionals, researchers, educators and students alike. There exist, however, distinct and significant tendencies within this development that require further investigation. This issue of AD takes on this task by examining one of the most promising trajectories in this area, the rise of intensely local architectures.

In his seminal essay of 1983, Kenneth Frampton redefined Critical Regionalism by calling for an intensely local approach to architectural design. He avoided a nostalgic or backward-looking attitude to regional traditions by placing an emphasis on contemporary construction and design techniques. Today, Frampton's legacy is regaining relevance for a specific body of work in practice and education focused on the construction of experimental structures. How might, though, this approach be further extended by the adoption of informed locally specific non-standard architectures? Could the most current design and production methods and tools be employed in order to respond to the specifics of local sites and settings? Could this ultimately provide the seeds for a compelling and alternative approach to sustainable design?

Contributors: Barbara Ascher, Karl Otto Ellefsen, Bijoy Jain, David Jolly Monge, Lisbet Harboe, Christopher Hight, Joakim Hoen, David Leatherbarrow, Mathilde Marengo, Gregg Pasquarelli, Sami Rintala, Søren S Sørensen, Defne Sunguroğlu Hensel, Jeffrey Turko.
Featured practices: the early Renzo Piano Building Workshop, Rintala Eggertsson, SHoP, Studio Mumbai, TYIN Tegnestue.
Works by pioneering integrated educational and research teams: e[ad] Escuela De Arquitectura y Diseño – Pontificia Universidad Católica de Valparaíso; Scarcity and Creativity Studio, Oslo; OCEAN Design Research Association and workshops directed by Shin Egashira.

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MAY/JUNE 2015 – PROFILE NO 235
PAVILIONS, POP-UPS AND PARASOLS: THE IMPACT OF REAL AND VIRTUAL MEETING ON PHYSICAL SPACE
GUEST-EDITED BY LEON VAN SCHAIK AND FLEUR WATSON

Around the world, a new architectural form is emerging. In public places a progressive architecture is being commissioned to promote open-ended, undetermined, lightly programmed or un-programmed interactions between people. This new phenomenon of architectural form – Pavilions, Pop-ups and Parasols – is presaged by rapidly changing social relationships flowing from social media such as Facebook, Twitter and Instagram. The nexus between real and virtual meeting is effectively being reinvented by innovative and creative architectural practices.

People meet in new and responsive ways, architects meet their clients in new forums, knowledge is 'met' and achieved in new and interactive frameworks. It contrasts bluntly with the commercially structured interactions of shopping malls and the increasingly deliberate interactions available in cultural institutions. It has its antecedents in market forums, and in the relaxed cafe society of urban Europe. A younger generation growing up in this rapidly changing relational web experience space and knowledge in ways that completely challenge the old formalities of fixed architectural types: schools, lecture theatres, concert halls, markets among other familiar programmes. These experiences imbue a new type of client; casually engaged, flocking, hacking, crowd funding and self-helping.

Contributors include: Rob Bevan, Pia Ednie-Brown, Roan Ching Yueh, Beatrice Galillee, Dan Hill, Martyn Hook, Minsuk Cho, Andrea Kahn, Felicity Scott, Akira Suzuki.
Contributing architects include: Alisa Andrasek/Biothing, Peter Cook/CRAB Studio, CJ Lim/Studio 8, Tom Holbrook/5th Studio, Matthias Hollwich/HKWN, Mamou-Mani Architects, Benedetta Tagliabue/EMBT.

ARCHITECTURAL DESIGN

GUEST-EDITED BY
NEIL LEACH

SPACE ARCHITECTURE: THE NEW FRONTIER FOR DESIGN RESEARCH

Space architects:
Constance Adams
Marc M Cohen
Ondrej Doule
Sandra Häuplik-Meusburger
A Scott Howe
Brent Sherwood
Madhu Thangavelu
Andreas Vogler
Robert Zubrin

Architects:
Bevk Perović Arhitekti
Dekleva Gregorič Arhitekti
Foster + Partners
Neil Leach
Greg Lynn
OFIS arhitekti
SADAR+VUGA

Forty years on from the first moon landing, architecture in Space is entering a new era. Over the last decade, there has been a fundamental shift in the space industry from short-term pioneering expeditions to long-term planning for colonisation, and new ventures such as space tourism. Architects are now involved in designing the interiors of long-term habitable structures in Space, such as the International Space Station, researching advanced robotic fabrication technologies for building structures on the Moon and Mars, envisioning new 'space yachts' for the super-rich, and building new facilities, such as the Virgin Galactic 'Spaceport America' in New Mexico designed by Foster + Partners. Meanwhile the mystique of Space remains as alluring as ever, as high-profile designers and educators – such as Greg Lynn – are running design studios drawing upon ever more inventive computational design techniques. This issue of AD features the most significant current projects underway and highlights key areas of research in Space, such as energy, materials, manufacture and robotics. It also looks at how this research and investment in new technologies might transfer to terrestrial design and construction.

SPACE ARCHITECTURE: THE NEW FRONTIER
FOR DESIGN RESEARCH

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