Future of Space

Space Settlement

Findings of the Mohammed bin Rashid Space Settlement Challenge

مؤسسة دبي للمستقبل
DUBAI FUTURE FOUNDATION

Space Settlement

The UAE's National Innovation Strategy highlighted the space sector, amongst clean energy, transportation, technology, education, health and water as one of the key pillars of innovation and growth for the future economy. Going forward the UAE's space sector will be critical in driving the UAE's broader national objectives including:

Building food security

The world's population will reach 9.1 billion by 2050: 34% higher than today increasing pressure on our food systems and requiring dramatically expanded production. Satellite observation has already increased the efficiency of agricultural production, through national schemes allowing farmers to use open source data to monitor local conditions. Space research will help us develop new technologies for efficient food production under extreme or constrained conditions.

Tackling climate change

Space research helps enable more sustainable living and can help us adapt to climate change. Space imagery is used in disaster monitoring, ecosystem dynamics and hydrology. Carbon capture technologies developed to recycle carbon dioxide on spacecrafts can reduce carbon emissions on Earth, as well as offer the possibility of recycling it into other critical resources such as oxygen, glucose and polymers.

Stimulating a constructive sense of wonder

Solutions to technical challenges cannot always be reached with a direct approach. Many challenges require the motivation of a higher goal that stimulates our imagination and demands that individuals and institutions think outside the box. The work of scientists and students pursuing space research has contributd to the creation of new materials, new design methods and more innovative technical systems that we use everyday such as laptops, smart phones, cancer imaging and laser technology. Perhaps equally as important, the dream of space offers a sense of purpose and urgency which few other professions offer. The sense of wonder, hope and shared optimism that space research represents can be a powerful force to inspire future generations to work together towards a common goal.

Laying a foundation for International Cooperation

Cross-border investment and collaboration in space research and exploration is growing visibly. This helps to build a shared sense of mission. In turn, this can contribute to the resolution of long-running geopolitical challenges. This shift will be crucial in order for countries to tackle global challenges.

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Introduction

During World War I, government demand for aircraft skyrocketed. Aviation companies responded to this sudden increase in demand, which fueled their rapid growth. When the war finally ended, this demand declined sharply and contracts for new aircraft were cancelled. Given that the market was just no longer profitable, aircraft manufacturing companies struggled to stay in business. The aviation sector was at risk of shrinking dramatically and potentially even disappearing.

However, government authorities in the United States saw the potential for commercial airplanes in another public service: the new airmail service provided by the Post Office Department (now known as the United States Postal Service) since 1918. The Air Mail Act of 1925, commonly referred to as the Kelly Act, allowed the postmaster general to contract commercial air carriers to deliver mail, letters, and packages. Postal delivery fueled new demand for airplanes, causing the aviation industry to grow once more.

Over time, the aviation industry began attracting talented engineers and entrepreneurs who proposed selling tickets to passengers to fly alongside the mail. Initially, many people were concerned about safety and continued to travel by ship. However, as the aviation industry grew, air travel became safer and more affordable, and passenger air travel increased steadily. By the mid-1930s, private airlines – TWA, Pan Am, Delta and others – attracted enough passengers to offset their operation costs.

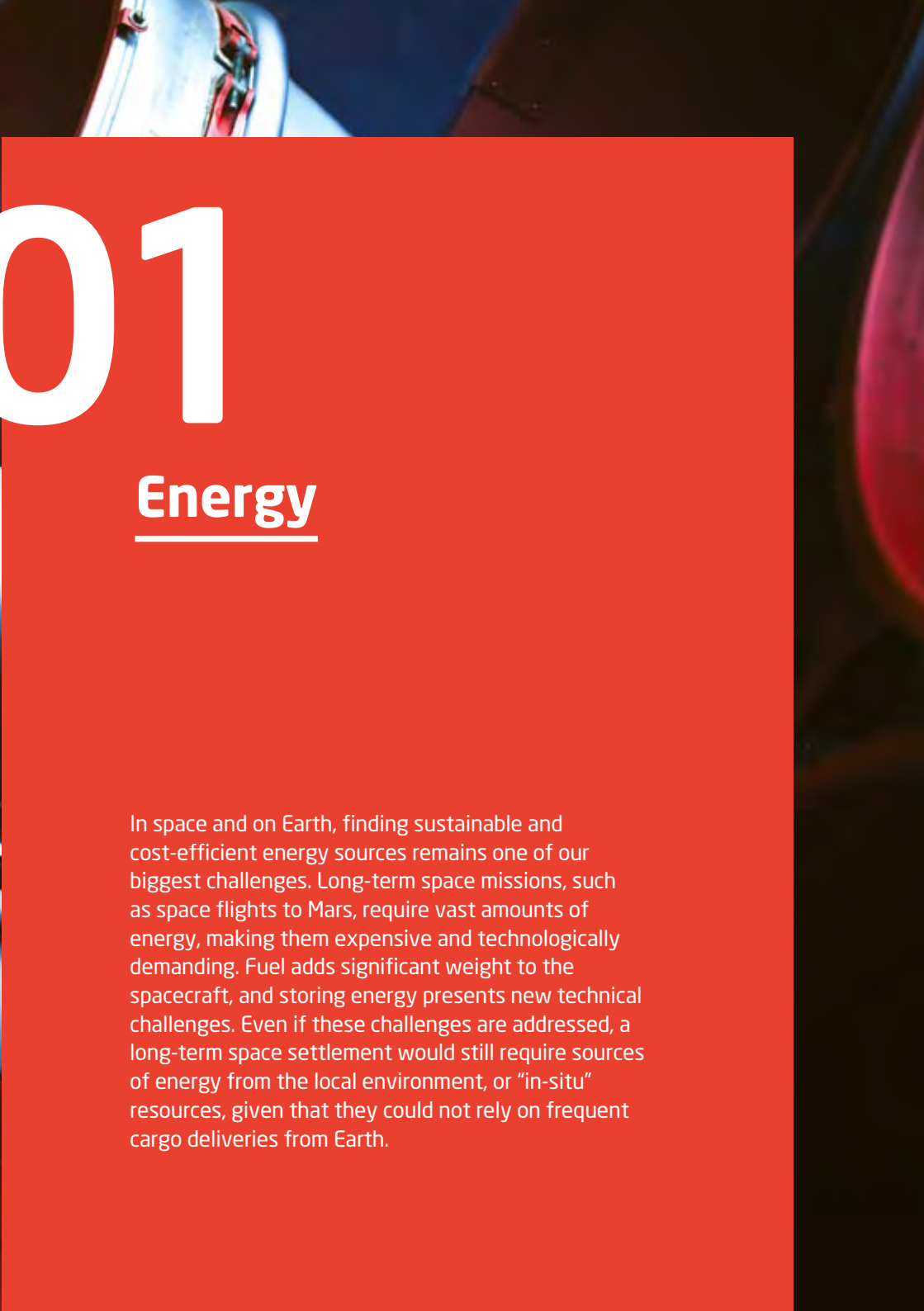
Passenger air travel now accounts for the majority of international travel and a significant share of domestic travel. Moreover, aviation is a critical sector in the global economy. It is responsible for about 1% of global GDP, supporting almost 3 million jobs according to the International Air Transport Association. Aviation contributes to productivity and commerce in most countries around the world.

The history of the aviation industry provides an important analogue for the space sector: the source, timing, and value of innovations cannot always be predicted, but it is a critical component of progress. Industries are not necessarily born ready for private sector investment, when the return on investment is too distant or not yet imaginable. Government demand – motivated by public values or the desire to improve public services rather than profit – can fill this gap. At the same time, the aviation industry's history highlights the value that comes from combining rather than separating commercial and government efforts, allowing the private sector to thrive following an initial contract with the government. Government funding for research is a critical channel through which countries can achieve longer-term goals and fuel innovation, growth, and development.

In this context, the Mohammed bin Rashid (MBR) Space Settlement Challenge sought to accelerate the gains of space research, support the UAE's vision of building a strong national space agency, develop a domestic space industry, and become a hub for scientific research and talent. In 2018, the MBR Space Settlement Challenge funded 35 research teams from private companies and academic institutions from countries all over the world to advance space research and develop technological solutions. The aim was not to control the development of the technology, but to ask the researchers to explain how a government grant would help turn their research into useful technologies for communities settling in space.

The challenge included research in various disciplines including science, mathematics, engineering, technology, economics, law, political science, and even art. The findings therefore address a number of questions that will not only be relevant to future space settlement, but also to issues that are already present on Earth, such as food and water scarcity, public health and policy, and sustainable energy.

These projects have now been completed. To access the full scientific papers please get in touch at research@dubaifuture.gov.ae. This report summarizes each of the 35 projects, dividing them into five thematic sections.



01

Energy

In space and on Earth, finding sustainable and cost-efficient energy sources remains one of our biggest challenges. Long-term space missions, such as space flights to Mars, require vast amounts of energy, making them expensive and technologically demanding. Fuel adds significant weight to the spacecraft, and storing energy presents new technical challenges. Even if these challenges are addressed, a long-term space settlement would still require sources of energy from the local environment, or “in-situ” resources, given that they could not rely on frequent cargo deliveries from Earth.

In order to address these challenges, a number of projects that the MBR Space Settlement Challenge funded looked at the potential for sustainable energy resources such as solar thermal energy, solar hydrogen from mined asteroids, and compounds found indigenously on Mars. Some of the projects advanced existing research on the potential sources of energy in space whereas others sought to test new theories. Most critically, however, much of the research has direct and indirect applications and lessons for Earth.

01

Combustion of Indigenous Martian Chemicals for Planetary Mobility

Abdul Ismail
Interplanetary Expeditions Ltd., University of Liverpool

In this project, researchers sought to find an economically and technologically feasible solution for long-term space missions by testing compounds found on Mars – a practice known as "in-situ resource utilization". This project expanded the evidence that carbon dioxide, which constitutes 96% of the Martian atmosphere, and magnesium (4% of Mars' soil) could be a critical source of fuel on the Red Planet.

Although there are several compounds found on Mars that can be used as propellants, many of them involve the use of cryogenics – meaning they need to be stored at an extremely low temperature. This makes these fuels very expensive.

The scientists tested a lower-performing but non-cryogenic alternative: magnesium metal powder (fluidized by nitrogen) suspended in carbon dioxide gas. They tried different ways to inject and arrange the particles in the gas. The team found that using soundwaves to levitate the magnesium atoms was a useful way to control them, before igniting them with a laser. They could then study the microscopic behavior of fuel particles during combustion, understanding the most efficient way to arrange them.

Fluidized metal powder propulsion systems have been investigated on and off since the 1940s, when engineers and scientists developed ballistic missiles, aerial ramjets, and submersibles. However, the concept only began to be explored in space flight research in the 1960s. Many technological challenges, such as combustion and cooling, have still not been resolved. This project increased our understanding of how to do this for magnesium and carbon dioxide, strengthening its case as a cost-effective Martian fuel.

Enabling Planetary Exploration Using Solar Hydrogen in Asteroid Regoliths

Dr. Martin Lee
School of Geographical & Earth Sciences, University of Glasgow

In this project, researchers assessed whether asteroids can be mined for hydrogen and water. These are vital for spacecraft fuels and would support longer-term missions or space settlements by providing local resources.

Until recent times, the effects of space weathering on asteroids were largely unknown. Any physical and chemical changes to asteroid surfaces were assessed by remote sensing, such as spectroscopy, using Earth-based telescopes and spacecraft. However, the Japan Aerospace Exploration Agency's recent Hayabusa mission collected and returned mineral grains from the Itokawa asteroid.

This provided an opportunity for the researchers in this project to use a new instrumental technique – called atom probe tomography – on asteroid samples. They were able to accurately measure the hydrogen and water levels held in silicate mineral grains. The team could then estimate the total availability of these resources on the asteroid, given the effects of space weathering on samples on earth. The preliminary work proving the feasibility of this project was presented at the 2018 Lunar and Planetary Science Conference. Understanding what these more accurate measurements mean for our models of asteroid structure is an ongoing process.

01

Solar Thermal Power for Space Settlements

Sarah Corbet, Joshua A. Keep, Jayden Kovacs, Francisco Macias, Shon Mori, Reece Otto, Augusto F. Moura, and Ingo H. J. Jahn
School of Mechanical and Mining Engineering,
The University of Queensland

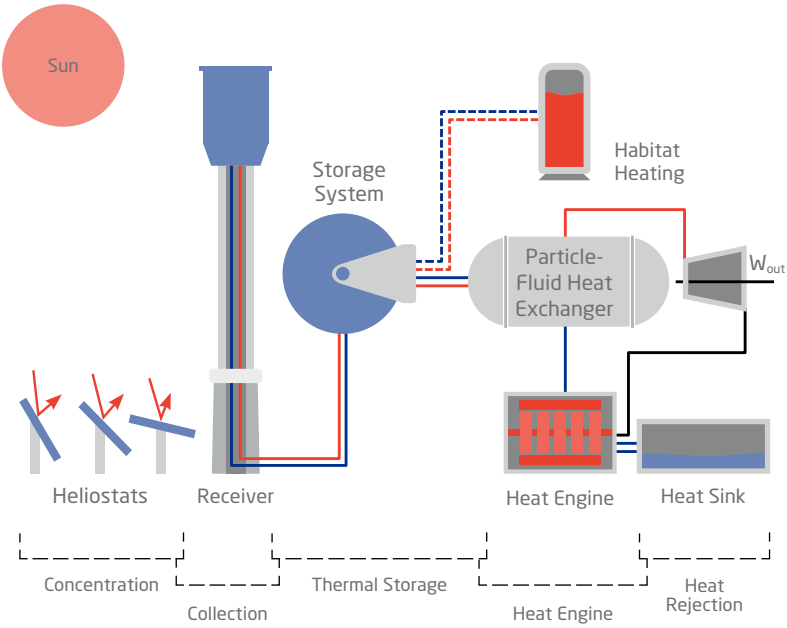
Researchers on this project developed a preliminary design study for an electrical power generation system to suit a small space settlement.

Although nuclear power, photovoltaics (PV), and batteries are the main technologies used to generate electricity in space systems, they degrade over time and are relatively high mass. For permanent space settlements, which will need continuous power, the project team used concentrated solar power in combination with thermal storage and a heat engine to build a power generation system.

The energy storage facility is built from locally sourced materials, and the high-tech components (heat engine, receiver, reflectors) are compact and light, allowing the system to be deployed easily in space settlements and offer high energy-conversion efficiencies. Concentrated solar power technology is also a potential solution to complement PV applications on Earth.

The study found that the heat exchanger would pose two of the most important challenges to realizing this technology. Using current science, it would have to be prohibitively large to operate at the required efficiency. There also has not been any engineering work done to understand how it could operate in alternative gravity.

FIGURE
Concentrated Solar Thermal Power Plant



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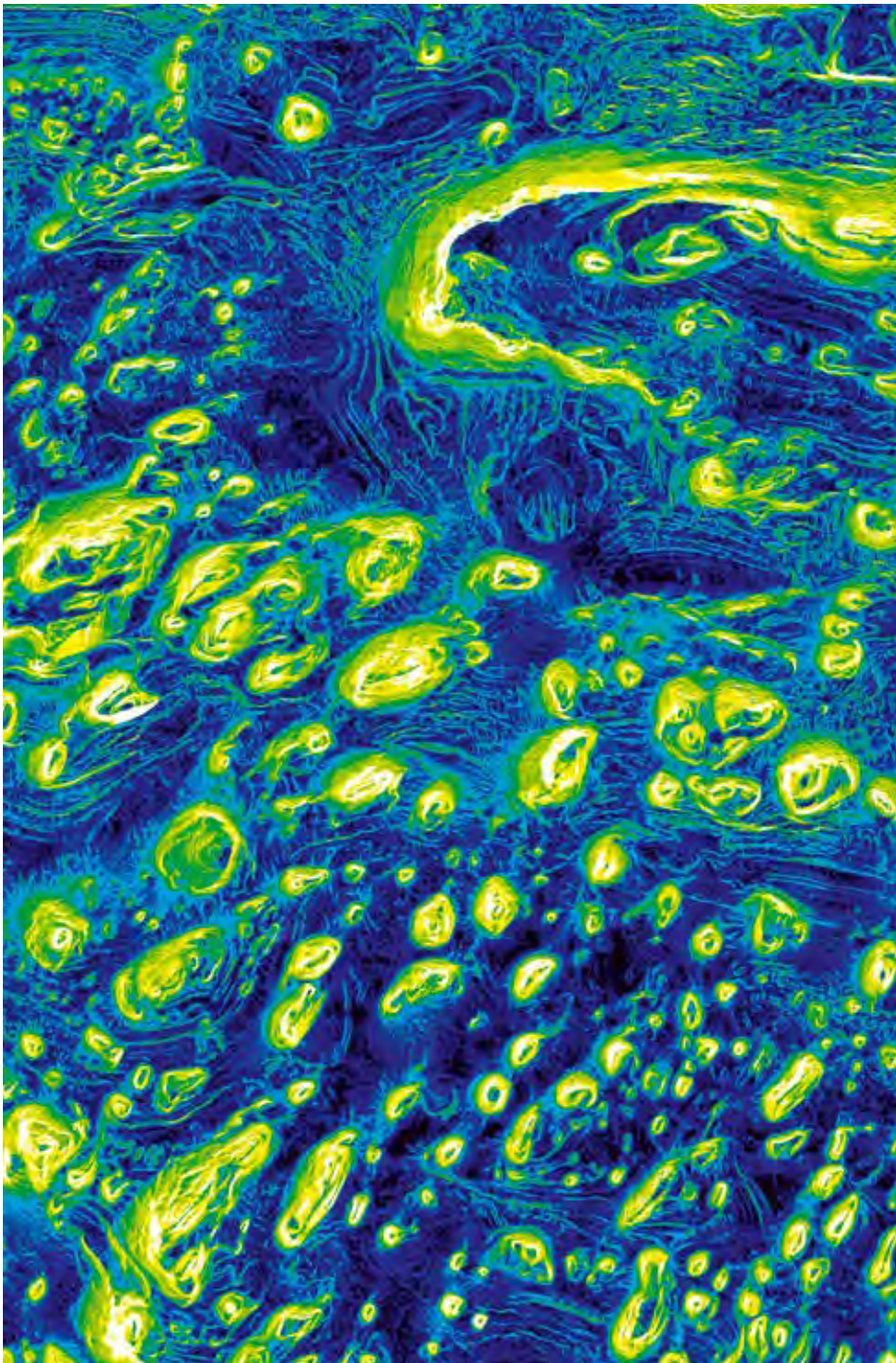


Using Microbes in Bioelectric Reactors to Extract Oxygen from Martian Soils

Martin Van Den Berghe, Joshua West, and Kenneth Nealson
Department of Earth Sciences,
University of Southern California

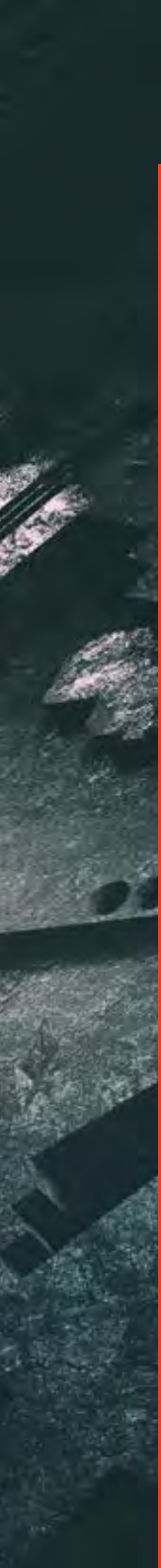
Generating oxygen will be one of the key challenges in developing a settlement on Mars given that CO_2 makes up 95% of the Martian atmosphere. However, scientists found that vast amounts of oxygen are held in the planet's soil, bound in ferric oxide minerals and perchlorate salts. Advancements in such microbiological research indicate that Mars' soil contains enough oxygen to support a long-term settlement on the planet.

In this project, scientists developed a bioreactor technology to extract oxygen by using bacteria that can grow on electrodes and dissolving specific mineral substrates in order to generate gaseous oxygen. They successfully demonstrated that a bioelectrochemical system can leverage cutting-edge developments in microbiological sciences to efficiently extract oxygen out of common, easily accessible Martian base materials.

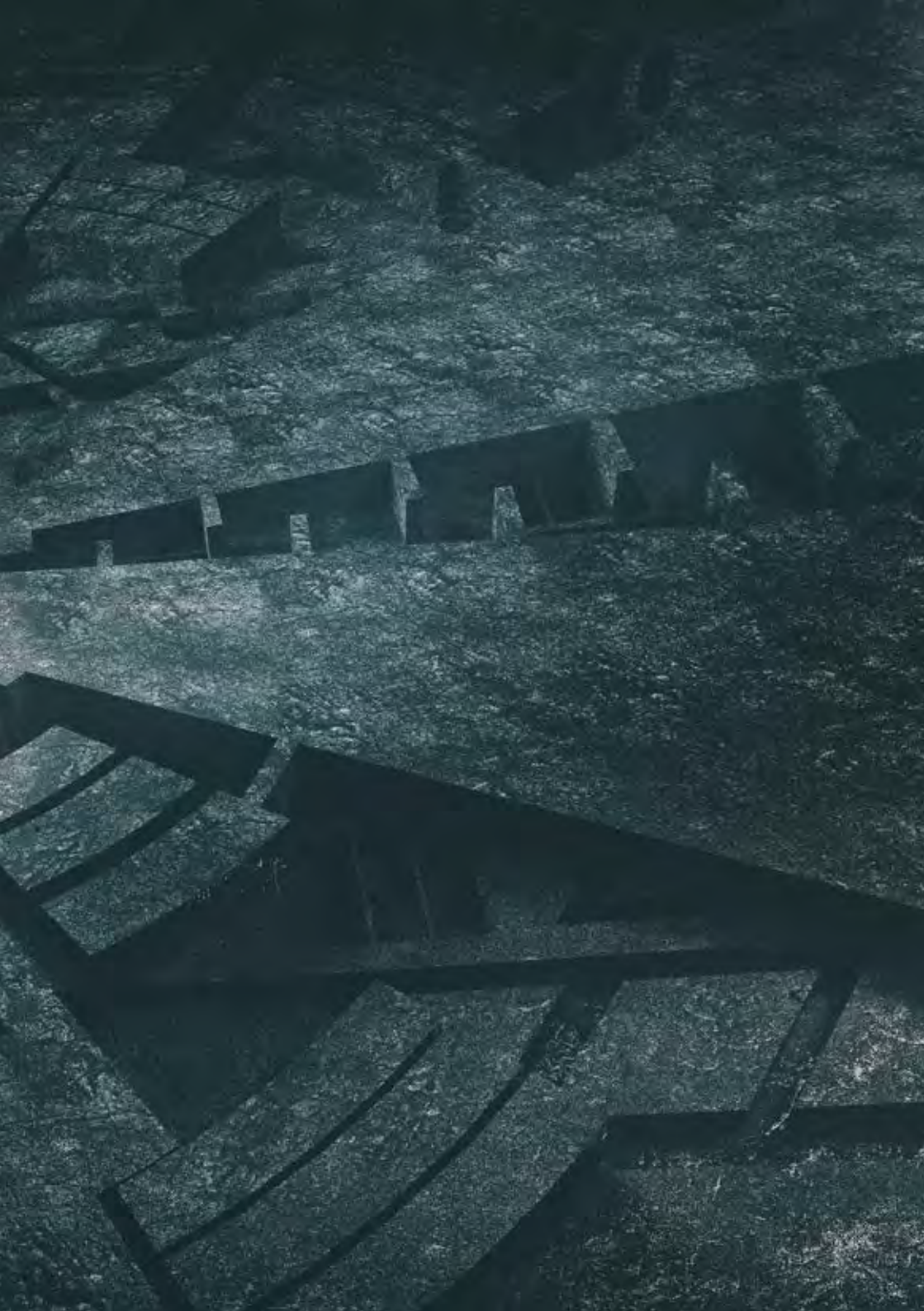
02

Construction

The construction of any long-term space settlement or base will require significantly advanced building technologies given that the basic physical properties of structures on Earth cannot be compared to those in space. To be feasible, built structures will have to be adapted to different levels of gravity, atmospheric pressure, and - most importantly -space radiation.



Given that such conditions would cause typical building materials to respond differently in space than they do on Earth, construction in space will require materials with entirely different chemical and physical properties.



02

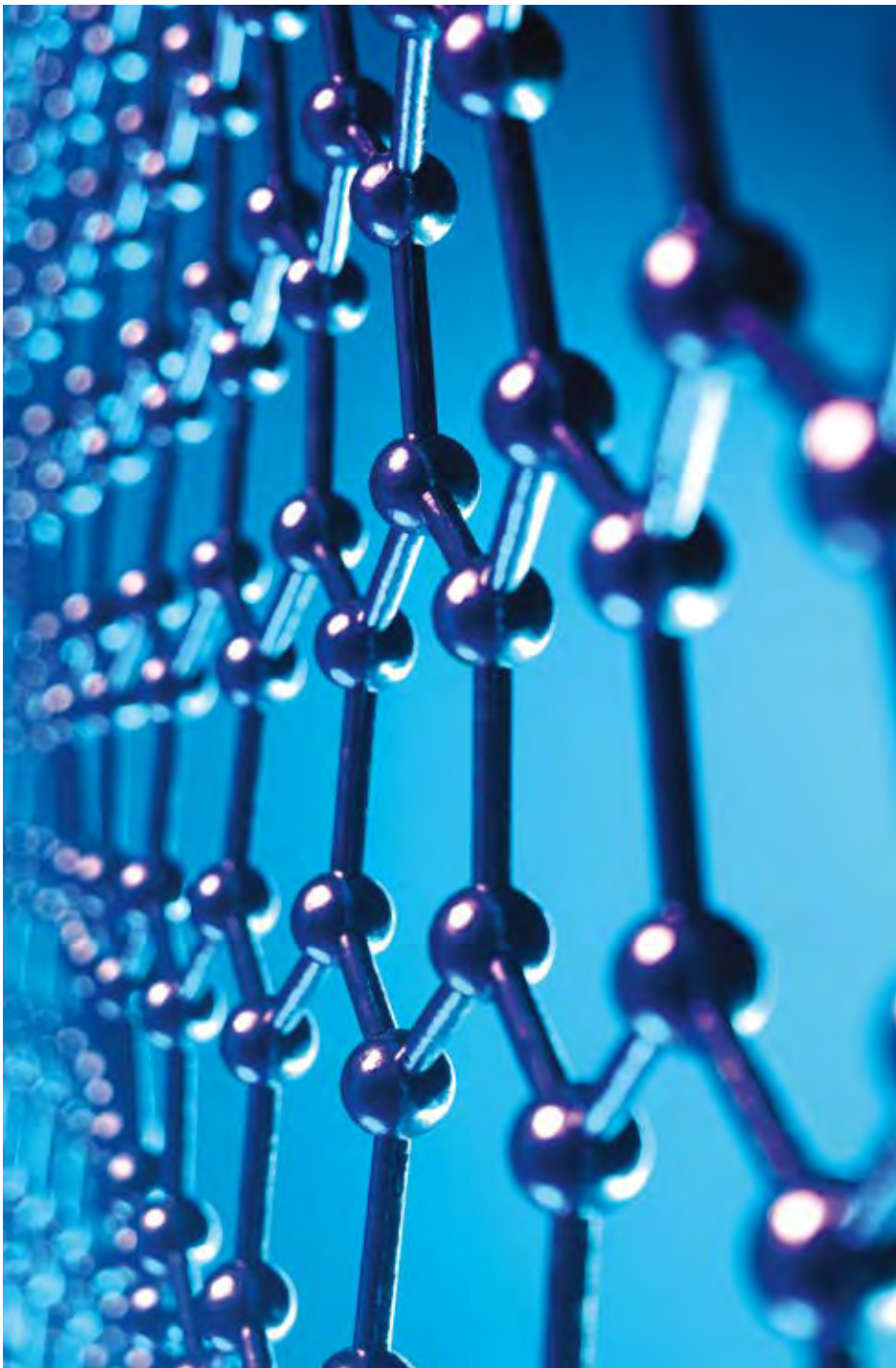
Space construction will also differ significantly from its terrestrial counterpart given that it will not be able to rely on human labor. Traditional building methods still require human labor, but given that it would be challenging to take enough workers from Earth on long-term space missions, the labor force would be strictly limited. This suggests that other methods of robotic construction that could be operated remotely might have to form the largest share of builders in space. These methods are also a key focus for research in space construction.

In this context, a number of researchers explored potential solutions for constructing space-proof buildings using alternative materials, the ideal living environment required to maintain space settlers' physical and mental health, robotic construction methods, and 3D-printing construction technologies.

Additionally, scientists also identified other terrains that could offer potential solutions for the construction of a human settlement on Mars. Some projects looked at underground tunnels that are found on Mars – called "lava tubes" – that could potentially be used as natural shelters for initial space travelers and eventually even space settlements. These tunnels would protect astronauts from surface radiation, drastic temperature swings, micrometeorite impacts, and rocket exhaust blasts. Some lava tubes on the Moon and Mars might also be cold enough to trap water ice, which, if actually present, might provide an essential resource. They may also be potential underground habitats for microbial life.

Other projects examined the potential for building space settlements or bases on near-Earth asteroids and sought to identify asteroids that could be likely candidates.

02



Graphene-enhanced Materials for Use in Space Settlement Applications

Dr. Robert Walsh, Darren Ansell, and Ben Watkinson
School of Physical Sciences and Computing, School of Engineering, University of Central Lancashire

Researchers from the University of Central Lancashire evaluated the possibility of using graphene-enhanced materials in a space settlement. Graphene is a form of carbon consisting of one-atom-thick planar sheets that are arranged in a honeycomb-shaped lattice. It is one of the lightest, strongest, thinnest materials that can conduct heat and electricity and therefore holds significant potential for use in construction and even equipment on Mars.

The project team examined how these materials react when they are exposed to the low temperatures and low-pressure environments they would experience on Mars. To test these materials, they sent high-altitude balloons more than 35 kilometers above the Earth's surface carrying graphene-enhanced antennae. The team found that there was no noticeable effect on the tensile properties of the graphene-enhanced materials, indicating that they can withstand low temperatures and low pressure and could therefore potentially be an ideal material for technical equipment on long-term spaceflights.

02

Autonomous Multi-robot Technologies for Mars Base Construction

Dr. Jekan Thangavelautham
Space and Terrestrial Robotic Exploration Laboratory,
University of Arizona

Researchers developed robots that can build different types of structures autonomously using in-situ resources.

Autonomous construction robot technologies are critical for infrastructure development in space settlements given the scarcity and limitations of human labor in this context. Additionally, these technologies address the various challenges faced in construction on Earth in remote and extreme environments where it is expensive or hazardous to transport, house, or utilize human workers.

This technology also offers several practical applications to construction on Earth. It provides construction companies, government-managed public works, and disaster management agencies the ability to build, repair, and upgrade canals, seawalls, or dams that are higher risk areas for human labor capital or infeasible for traditional construction methods.

Designing a Martian House

Prof. Lucy Berthoud, Ella Good, and Nicki Kent
University of Bristol

In this project, artists collaborated with scientists to design and build a house that could be physically ideal for living on Mars. The team held a number of workshops with architects, geologists, and engineers that specialize in developing bases in extreme environments. Through these workshops, the team designed a house that operates using closed-loop systems and recycled waste products into energy sources with the aim of making it completely sustainable. In the face of growing global concerns about climate change, this project addresses the urgent need for sustainable housing developments for our future on Earth.

The team also brings attention to the "human" element of future space settlements by emphasizing the significance of living spaces that support the mental and psychological health of people living in challenging environments. For example, the team consulted experts in polar and arctic construction to estimate and define the ideal ratios of personal and social space to ensure astronauts living on Mars will maintain good mental health and emotional wellbeing.

02

Automated Construction Using Interlocking Blocks

Prof. Devin Balkcom and Yinan Zhang
Dartmouth University

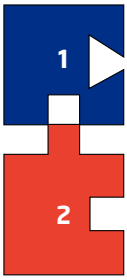
In space, environmental conditions such as atmospheric pressure, gravity, erosion, and friction are not comparable to those on Earth and therefore do not allow the use of traditional building materials. To address this challenge, this team of researchers designed interlocking construction blocks that can be assembled by robots. These blocks do not rely on friction, glue, or connectors to hold together. Instead, they use sequences of joints in different directions, arranged in a circular pattern, so that later blocks prevent earlier blocks from moving.

This project addresses the urgent need for automated construction, which will not only be critical for building space settlements but also for advancing construction technologies on Earth. Although many consumer devices, ranging from cars to cell phones, are designed for easy assembly in robotic factories, building structures on Earth still uses technologies developed for humans centuries ago. Simplifying construction for robots is crucial for building on Mars where human labor will be limited.

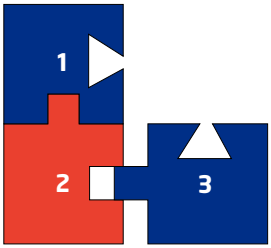
The interlocking blocks developed in this project also address some of the main gaps seen in existing space settlement construction, such as 3D printing. Existing 3D technology can build small shapes quickly, but it is not ideal for larger structures. Given that this project's interlocking blocks are made in standardized sequences, they are ideal for automated robotic construction and are easy to rebuild, repair, alter, and recycle.

FIGURE

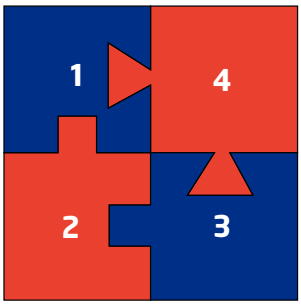
Phase 1



Phase 2



Phase 3



The interlocking blocks use sequences of joints arranged in a circular pattern so that later blocks prevent earlier blocks from moving. Since they don't require any friction or adhesive, they can easily be assembled by robots

02

Multiphysics Simulations of the Behaviors of Martian Concrete

Yifei Ma
School of Civil and Construction Engineering,
Oregon State University

In this project, researchers tested the performance of "Martian concrete," or sulfur concrete, for space construction. Martian concrete has a number of characteristics that make it ideal for extraterrestrial construction, such as high strength and durability, excellent resistance to acid and salt exposure, and low water permeability. However, given that the extreme environmental conditions in space cannot easily be reproduced on Earth, assessing the workability of Martian concrete is challenging.

To tackle this challenge, the project team tested the performance of this concrete by using computational modeling to implement multiphysics simulations. They estimated stresses induced by temperature variation and erosion caused by seasonal dust storms that may lead to serious structural problems.

Mars Human Landing Sites: Resources, Safety, and Science Return

Maurizio Pajola
National Institute for Astrophysics,
Astronomical Observatory of Padova, Italy

In this project, researchers evaluated potential landing sites on the surface of Mars that could provide an ideal location for a sustainable settlement. By using the first published Water Equivalent Hydrogen (WEH) maps produced by Jack Wilson et al., researchers identified locations on the planet's surface that are characterized by subsurface water ice and/or "hydrated subsurface minerals."

Through these WEH maps, researchers assessed settlement locations and certified areas with the requisite landing and roving safety requirements, confirming that they are 100% safe. The evaluation of all the identified sites was based on their scientific merits, with an emphasis on areas that show clear morphological evidence of past standing bodies of water, fluvial activity, and/or surface ices coupled with subaqueous or hydrothermal sediments. Particular attention was given to how the resources could be acquired and the impact it would have on the Martian environment.

02

Radiation Shielding with Specific Application to the Moon and Mars Base Analog

Dr. Christiane Heinicke, Sumana Mukherjee
Center of Applied Space Technology and Microgravity (ZARM), University of Bremen

Mars, or any planetary body that does not have a magnetic field or substantial atmosphere such as the Moon, is continuously bombarded by radiation through solar wind, galactic cosmic radiation, and solar particle events, which poses significant risks to astronauts' health. In this project, researchers looked at potential solutions for radiation shielding.

Currently, NASA limits astronauts' radiation exposure to 0.5 sieverts per year (Sv/year) to manage the risks of adverse health effects. However, radiation shielding could remove the risks associated with space radiation and strengthen the case for long-term space settlements. Researchers on this project worked toward developing the early stage technologies for radiation shielding using FLUKA[i] software simulations that could be used on Mars and the Moon. The team first conducted a trade-off analysis based on criteria such as production cost, launch cost, installation cost, shielding effectiveness, and structural impact on the habitat. They then developed simulations to optimize the most promising shields in lunar and Martian surface habitat designs.

Although the designs focused on the Mars and Moon habitat recently built by the Center of Applied Space Technology and Microgravity in Bremen, they are also applicable to other stations.

i FLUKA is a multi-particle transport code that simulates the interaction and transport of particles and nuclei in matter. The project team used it to investigate the shielding capabilities of different materials and their required thicknesses.

Terraforming of Mars Through Magnetic Shielding with an Artificial Magnetosphere

Chuanfei Dong
Princeton University

Earth is fortunate to have vast webs of magnetic fields surrounding it, without which much of its atmosphere would have deteriorated by solar winds, preventing sustainable life on the planet. Unmagnetized planets, like Mars, are especially vulnerable to atmospheric scavenging because solar wind interacts directly with the upper atmosphere due to the lack of an intrinsic magnetic field.

In the early period of its history, it is likely that Mars did have magnetic fields, making its climate warm and moist like the Earth's. If Mars still had a functioning magnetosphere, it would be protected from solar winds and space radiation. This possibility raises an important question: if such a magnetosphere could be developed, would Mars have a thicker atmosphere, warmer climate, and liquid surface water, making it a habitable planet?

In this context, researchers looked at the potential of "terraforming" Mars using magnetic shielding created by an artificial magnetospher using the BATS-R-US model.[iii] Preliminary studies show that Mars could be protected from solar wind erosion by positioning a magnetic dipole shield at the Mars L1 Lagrange point,[ii] supporting the evidence that the Red Planet could be terraformed, or transformed into a more habitable, Earth-like environment.

ii A location where the combined gravitational forces of two large bodies, such as Earth and the sun, equal the centrifugal force felt by a much smaller third body

iii BATS-R-US, the Block-Adaptive-Tree-Solarwind-Roe-Upwind-Scheme, was developed by the Computational Magnetohydrodynamics Group at the University of Michigan

02

Choosing a New Home: How to Determine Which Asteroid to Settle

J.L. Galache
Aten Engineering Inc.

In this study, researchers took a preliminary step toward identifying any known asteroids that may be suitable for settlement. The team selected asteroids according to a set of criteria, including how easy they are to reach, how often the trip can be made, and the asteroids' size. They also considered what the asteroids are made of to determine if they could be mined for valuable resources. The team also determined the potential to speed up an asteroid's spin such that a settlement on its surface, or in a ring around it, might experience artificial gravity through centrifugal acceleration. They found that near-Earth asteroids (NEAs) make the best candidates. NEAs require the least amount of energy to visit, but they also have the longest synodic periods – the amount of time it takes the asteroid to reappear at the same point. This means that any settlements on these asteroids must be self-sufficient from the moment of landing because the time between launch windows is many years – even decades – long. These settlements would not be able to get resources from Earth for long periods of time.

To support the preparation of an asteroid settlement's plans, the key information researchers need to know is how often the asteroid is accessible, its size, composition, and spin period. In this context, there are several large asteroids in the Main Belt that may be suitable. However, the primary challenge researchers identified was that the known large asteroids that could be suitable for a settlement, such as Eros 433, 1204 Renzia, 1034 Mozartia, and 2717 Tellervo, do not contain hydrated minerals from which water could be extracted. Without water, these settlements could never be self-sufficient.

The project team concluded that for further exploration of asteroids for mining or settlement, a different strategy for observation and data collection needs to be adopted. Without knowing the size of an asteroid to an accuracy better than the current ± 50%, it is impossible to determine whether it will be profitable to mine or not, and with poorly constrained orbits, spacecraft cannot be sent to them.

Living on an asteroid is still far in the future, and there are several obstacles that keep suitable candidates from even being identified, let alone settled on for years at a time. However, these obstacles should not deter us, but rather inspire us to work harder toward the goal of making humans a species that lives both on and off the Earth. According to researchers, it would take at least 10 to 15 years to develop a suitable catalogue of NEAs that could be potential candidates given that asteroids only appear a few days or weeks a year and commonly not for a few years.

02

Sustainable Space Settlement: Stability Analysis of Lava Tubes

Anahita Modiriasari, Anthony Bertels, Audai K. Theinat, Amin Maghareh, Antonio Bobet, Henry J. Melosh, Shirley J. Dyke, and Julio Ramirez
Purdue University

To develop a feasible permanent subsurface settlement design, a research team from Purdue University assessed the structural stability of lava tubes on the Moon and Mars for long-term settlements.

Researchers conducted numerical examinations of the static and dynamic stability of the lava tubes considering their geologic origin, which determines the mechanical properties of the lava and the size and shape of the tubes. The team also estimated geostatic stresses compatible with the geological history of the tubes, and more importantly, their ability to withstand hazards such as meteorite impacts, seismic activity, and drastic temperature fluctuations.

For example, when meteorites impact the lunar surface, the kinetic energy from the impact is partitioned into three forms: cratering excavation, visible light, and seismic waves. Researchers were therefore able to develop a testing model that simulates the characteristics of typical lava tubes, which will allow scientists to determine the feasibility of lava tubes as potential candidates for space settlements.

Are the Caverns in Mined Asteroids Suitable for Space Colonization?

T. I. Maindl, B. Loibnegger, and R. Miksch
Department of Astrophysics, University of Vienna

In this project, researchers developed methods to create artificial gravity that could support space settlements in extraterrestrial environments such as on asteroids.

Most identified asteroids are hundreds of meters in diameter. Caverns inside these asteroids could provide a possible habitat for a space colony hosting a few hundred inhabitants. However, given that most asteroids are found to have very low gravity, the project team used numerical simulations to investigate the stability of a hollow asteroid when put into rotation at a rate that provides a sufficient fraction of Earth's gravity.

The team used smooth particle hydrodynamics to model a range of different ductile and brittle materials with varying porosity. These simulations were then applied to estimate the stability of rotating and non-rotating hollow bodies, allowing the researchers to investigate the rate of angular momentum change necessary to spin the body up to the required rotation rate.

02

Habitability of Lava Tubes on the Moon and Mars

Dr. Pascal Lee
SETI Institute, Mars Institute

To investigate the potential of lava tubes to serve as areas for future space settlements, scientists conducted systematic surveys of what is known and unknown about the geotechnical characteristics of lava tubes on Earth and the conditions under which they harbor ice.

Scientists visited sections of the Lofthellir Lava Tube Ice Cave complex in Iceland – one of the few ice-rich lava tube systems known on Earth – to observe the characteristics of ice formed in these tubes, which provided an analog for lava tubes on Mars. If ice accumulated inside lava tubes on the Moon or Mars, it would be an important source of water for space settlements. However, this accumulated ice would also come with risks. Gravity might produce underground micro-glaciers, while gelifraction – rock fracturing caused by water freezing – could cause rock falls and collapse in the lava tubes.

03

Food and Water

Another key issue addressed by a number of space researchers is the requirement of sustainable food sources to provide settlers with adequate nutrition, given that it will not be environmentally and economically feasible to regularly import food from Earth. Any remote station located on Mars, or possibly even the Moon, will vitally depend on its local food production facilities.

Efficient food production under extreme or constrained conditions is a critical area for food security on Earth as well given the expected impact of climate change on agricultural food production relative to population growth.

03

A Bioreactor to Produce Algae

Mate Ravasz, Daniel Budinov, Stephan Matthiesen, and Jiri Jirout
University of Edinburgh

In this project, researchers developed an automated greenhouse that incubates and cultivates algae. Algae are expected to be an important food source for future space settlements, as they are rich in protein and contain a range of useful lipids and carbohydrates. They can grow in liquid, which is much easier to manipulate by machinery than a tree or bush rooted in the ground. They produce no inedible biomass, use water effectively, and harvest light with high efficiency.

The project team designed and built a "smart bioreactor" that grows algae. Sensors inside the system monitor the culture and send data to a remote computer, from which a user issues commands so that the bioreactor can make any necessary adjustments to control the growth of the algae. This technology enhances the efficiency of algae production. It uses light that emits only the frequencies that the algae need to grow, reduces energy consumption, and employs more efficient control mechanisms.

Algae are one of the most efficient producers of biomass from inorganics. Researchers expect these plants will be particularly useful for long-term space missions and settlement.

03

Aeroponics in Space

Dr. Kamil L. Janiak
Wroclaw University of Science and Technology

This project used grey water – in this case waste water from a shower – to grow plants through an "aeroponic" system, which maximizes the use of the limited water supplies that would be available to early Martian settlements.

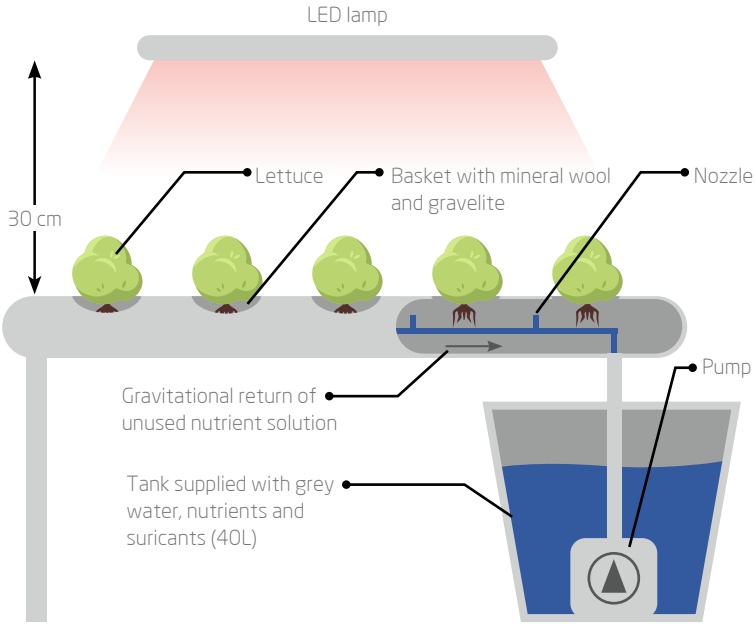
In traditional soil cultivation, 85% of water is lost through evaporation. Aeroponics suspends plants in the air without any soil and uses a fine mist to provide them with water and nutrients. This requires less water, resulting in reduced evaporation, and produces higher yields.

According to the researchers in this project, one ton of lettuce grown through the aeroponic system uses only 10 liters of water, compared to the 80 to 100 liters used in soil cultivation. The system also offered a better alternative than hydroponic cultivation by making it easier to monitor nutrient and pH levels.

The team tested the system on lettuce plants. They found that the plants could survive if they were first fed clean water for at least one week and then switched to grey water. However, even in this case, the plants grew slower.

FIGURE

Aeroponic Model



03

Farming Water on Mars

Javier Martin-Torres
Luleå University of Technology

In 2015, scientists noticed that certain salts found on the surface of Mars could absorb water vapor from the atmosphere, then "melt" into water when the temperature rises. However, this water only exists as a liquid temporarily – it goes from solid ice straight to vapor in a matter of seconds thanks to the planet's extreme environmental conditions. Atmospheric pressure is significantly lower on Mars (7 to 10 millibars) and the temperature generally ranges from a low of -90°C to a high of 0°C. If astronauts could find a way to collect this vapor, water could be harvested and eventually used to support life on the planet.

In this project, researchers used various deliquescent salts – substances that absorb moisture from the air at specific temperatures and humidity levels – to develop "water farms." The best salts absorbed enough water from the air that they turned into a salty water solution once a certain temperature or humidity level was reached, from which water can be extracted.

This water-farm technology could have implications for long-term Mars exploration and settlement, as well as for displaced communities living in extreme conditions on Earth.

Bionic Plants

Dr. Tara Karimi and Moji Karimi
Cemvita Factory

A team from Cemvita Factory prototyped a technology that replicates photosynthesis – the process by which plants take in carbon dioxide and water and turn it into oxygen and glucose.

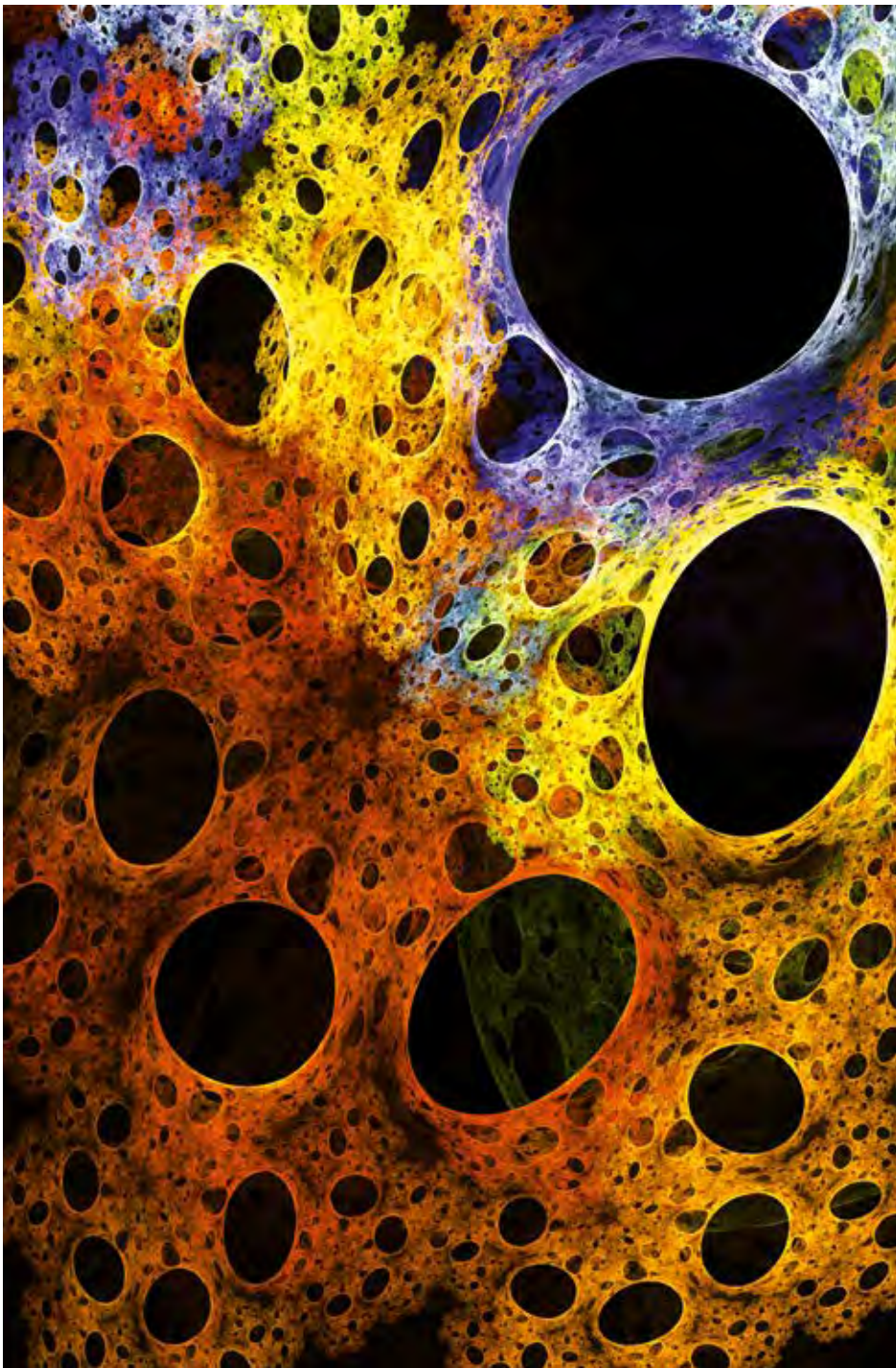
Astronauts typically breathe out one kilogram of carbon dioxide every day, which could be collected, processed, and recycled into compounds that are useful in space travel. Given that carbon dioxide also makes up 95% of the Martian atmosphere, this method suggests that space settlements in the future could create their own oxygen, glucose, and other compounds from just the air around them.

This technology might be even more critical for challenges on Earth, such as reducing carbon emissions to tackle climate change.

Many countries incentivize companies to reduce their carbon emissions by offering tax credits. Companies are therefore increasingly using carbon capture technology to remove carbon dioxide from the air and store it underground, which costs about $100 per ton. Using this prototype technology, companies can capture their exhaust gases directly, reducing the cost to $30 per ton.

The prototype developed for this project would not only reduce the cost of carbon capture, but would also allow firms to recycle carbon dioxide into other useful materials.

03



Mushrooms on Mars

Dr. Gene Giacomelli, Dr. Barry Pryor, and Sean Gellenbeck
University of Arizona

To reduce waste from inedible biomass and provide astronauts with high-quality protein, a team of researchers from the University of Arizona explored the possibilities for growing mushrooms in a greenhouse on Mars.

Food crops typically have edible parts with high nutritional content and inedible parts, such as the stalks and stems, that typically go unused. In space settlements, it will be critical to reduce waste and recycle as many resources as possible.

To address this issue, researchers devised a solution that uses mushrooms as "biological recyclers." The fungi are grown using the inedible leftovers from food production. They then become a sustainable secondary food source with a high nutritional value.

In addition to solving challenges of space settlement, subsystems such as this one will be useful in areas on Earth where resources are scarce.

03

Algae on the Moon and Mars Ensure Astronaut Survival

Dr. Gisela Detrell, Johannes Martin, Jochen Keppler, and Harald Helisch
Institute of Space Systems, University of Stuttgart

Microscopic algae, or microalgae, could potentially be a great resource for supporting long-term space missions, as it consumes CO_2 while producing oxygen and food. This project explored the key challenges related to implementing microalgae as a part of a life support system for a base on the Moon or Mars.

Researchers selected a flat-plate airlift photobioreactor as the most promising system by which to cultivate microalgae. In this system, CO_2-enriched air is released in through the bottom and the gas bubbles rise to the top, distributing the air and mixing the algae culture. Given that this system relies on gravity to push the bubbles to the top and the Moon and Mars have different gravity levels compared to those on Earth, the reactor had to be adapted to make it suitable for a Lunar or Martian settlement.

Through this research, scientists were able to develop the preliminary design that satisfies set criteria for liquid flow inside the reactor, the light/darkness cycle frequency, and the light to darkness ratio. The simulations proved that such a system can be adapted according to the environmental conditions, although further studies will be required to develop an optimal design for the bioreactor.

Microgreens Under Altered Gravity in Space Life Support Systems

Khaled Y. Kamal
Zagazig University

According to previous research, the microgreens of plants from the *Brassica* genus, which includes vegetables such as cabbage, broccoli, Brussels sprouts, and cauliflower, could provide an important source of nutrition for long-term space missions given that they can be grown in controlled environments under artificial light from LEDs.

In this project, researchers assessed the ideal controlled environmental conditions required for a growth chamber to cultivate *Brassica* microgreens with the requisite nutrient quality. The team grew 30 different species under conditions that replicated a typical space mission, including gravitational alterations, and examined the plants' yield, growth, and photosynthetic activity under green, red, and blue LEDs. They found that Tuscan kale, red cabbage, tatsoi, purple kohlrabi, and green cabbage grew best under these simulated conditions. The study also revealed that gravitational alterations did not have any significant impact on the plants' growth or morphological measurements.

03

Improvement and Testing of the Fog Shower for Future Microgravity Tests

Jedrzej Gorski, Klaudia Dradrach, and Jakub Falacinski
University of Wroclaw

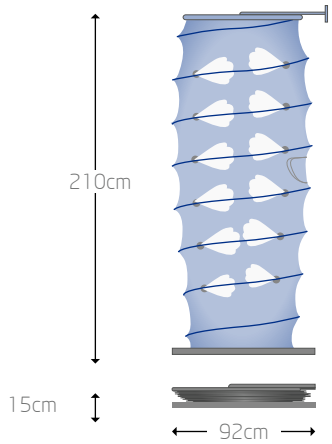
Maintaining astronauts' physical and psychological health, hygiene, and sanitation are key components of space flights, particularly deep space missions that can take up to several years. However, bathing in space poses some significant challenges. Without gravity, water particles clump together and stick to whatever surface they encounter first, rather than rolling off like they do on Earth. Using water condensates, such as fog or mist, rather than jets of water, presents a promising solution for bathing in zero gravity while also conserving water.

The project team from the University of Wroclaw advanced the development of a fog shower system prototype that could be used in zero-gravity conditions. It uses the physical properties of water mist to provide an equivalent system that reduces water consumption by more than four times typical shower systems.

The prototype also responds to the pressing need for water conservation, which is a critical requirement not only on long-term space missions but also in remote or arid areas on Earth. Previous design prototypes were tested in Mars analog simulations at the Austrian Space Forum in 2015 and the Mars Desert Research Station in Utah, United States, in 2017.

FIGURE
Fog Shower

The project team from the University of Wroclaw advanced the development of a fog shower system prototype that could be used in zero-gravity conditions

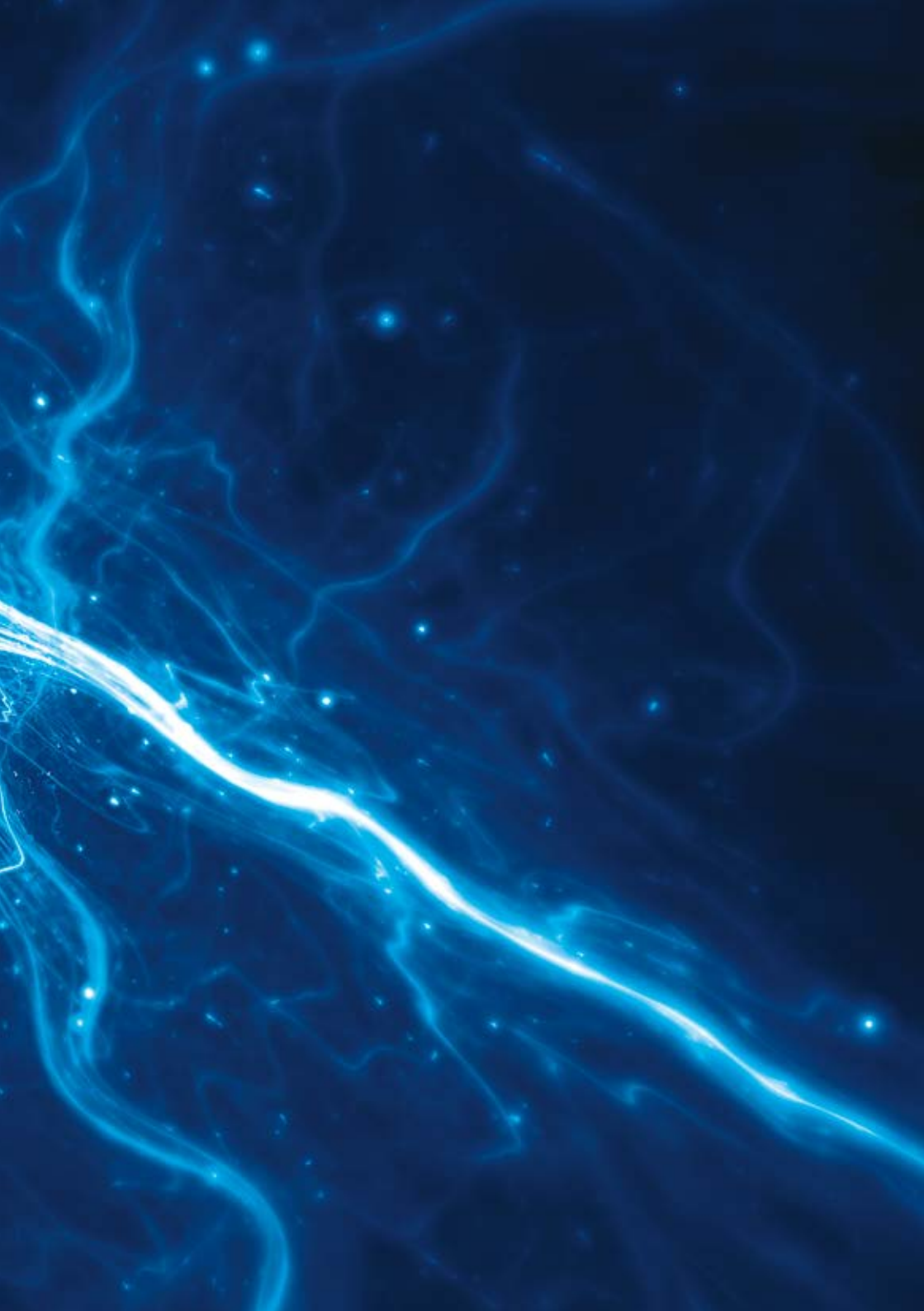


04

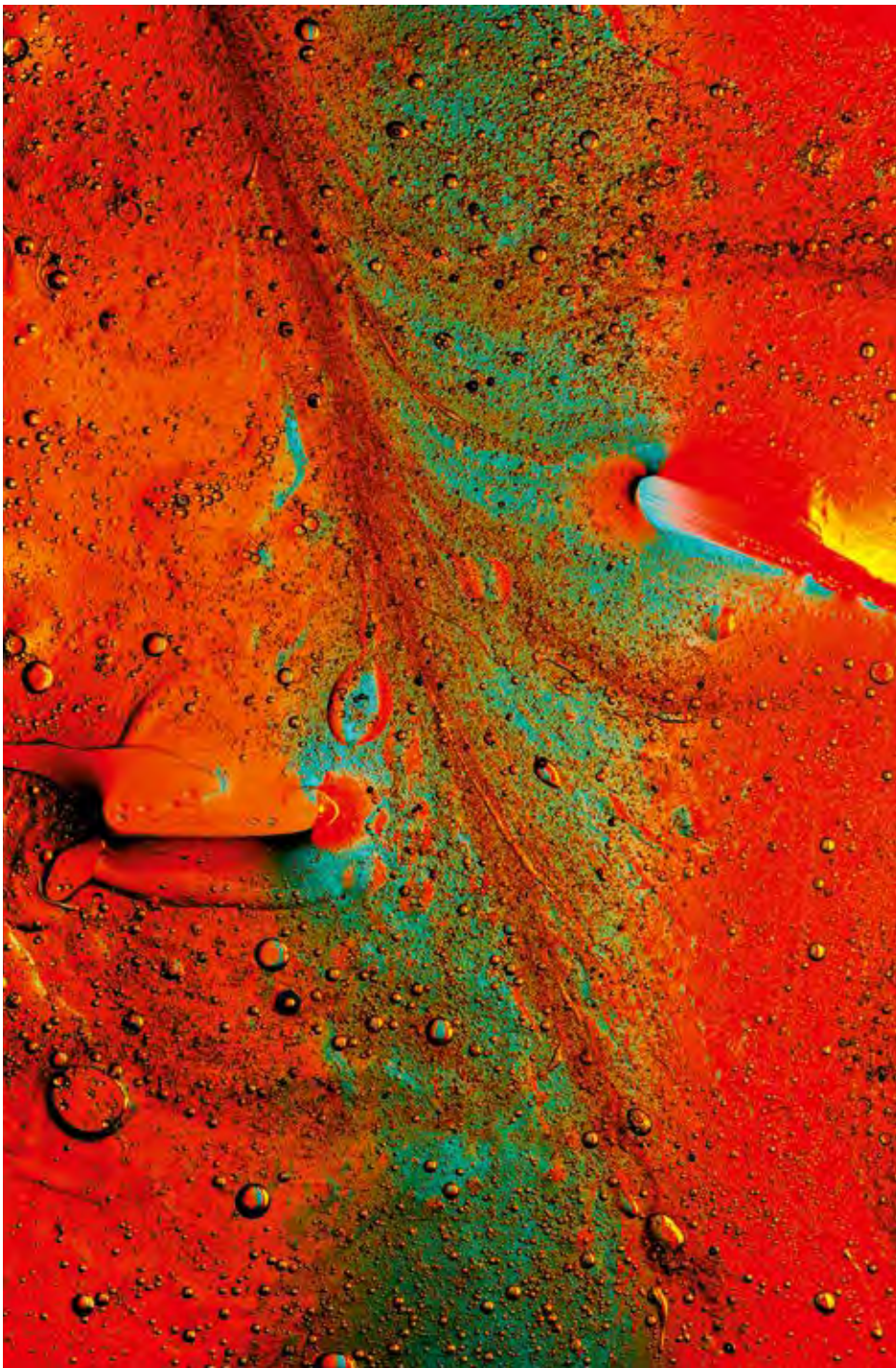
Policy

In addition to the various scientific hurdles that still need to be overcome for deep space exploration, the discovery of new terrains and materials raises several questions around the potential legal and policy implications for governing future space settlements.

Several projects looked at the various frameworks that could be used to build policies for space settlements by comparing existing international regulations for extreme environments, such as Antarctica and other areas of international cooperation, to future space settlements.



04



Mars Antarctica: Learning from an Antarctic Base Management

Federico Caprotti
University of Exeter

For this project, a research team from the University of Exeter brought together social scientists, environmental scientists and writers, and delegates from the British Antarctic Survey and the UAE's Emirates Mars Mission to discuss if existing policies and regulations in Antarctica could inform the regulatory and governance frameworks of near-future Mars settlements.

The workshop, which was held at Siemens' future cities-focused Crystal facility in London, explored how lessons from Antarctica could be applied to space settlements. Antarctica is unique in that it is Earth's only continent without a native human population and it is governed by an internationally agreed set of regulations – the Antarctic Treaty System. Antarctic bases have many similarities to potential Mars settlements: they exist in extreme environments, are technically complex and reliant on a technological support system, are crewed by a base crew that cannot leave the base for long periods of time, and are very far away from the nearest human settlement.

Although Antarctic bases face risks and constraints that would also be faced by Mars settlements, researchers determined that the magnitude of risks faced on Mars are significantly higher than on Antarctica. They noted a range of issues – psychological, technical, and legal – that will need to be rooted in the international policy environment.

One of the project team's key recommendations was to establish a center of research that will bring together corporations and research units active in robotics, artificial intelligence, advanced materials, virtual reality, and aeronautics, among other areas, to inform policy decisions for future space settlements.

04

Robust Control of Population in a Bounded Habitat

Jordan Kralev
Technical University of Sofia

The size of a future space settlement will have to be limited relative to how many people the habitat can host and how many people it can sustainably provide resources for. Therefore, it will be critical to develop an extremely efficient food production system. This project modelled a future space settlement in terms of the food production facility required to support a set population size.

A software simulator allowed the project team to demonstrate how an isolated population could survive, or potentially become extinct, in a restricted area depending on the habitat size. A spatial, nonlinear, dynamical population model accounted for growth, diffusion, and competition for resources between individuals in an isolated population. A number of theoretical models exist to explain environment spatiotemporal structure, proving that habitat size plays a crucial role in the fate of a population. In all cases, models show that the habitat must have a minimum size to ensure population survival.

In order to estimate this optimal balance between population size and the land area needed to generate resources for this population, this project's team developed mathematical formulae to calculate how populations and habitats in space settlements could be scaled or restricted.

Socioeconomic Population Planning for Future Space Habitats

M.B.N. Kouwenhoven, Don Eliseo Lucero-Prisno III, Xu Lin, Jiangchuan He, and Wei Hoa
Xi'an Jiaotong-Liverpool University

Researchers from Xi'an Jiaotong-Liverpool University used dynamic population modelling to illustrate different scenarios for the growth and evolution of a long-term settlement on Mars. The team imagined the initial communities that could be established by early astronauts and how these could gradually grow into larger colonies through typical population growth dynamics that account for birth and mortality rates relative to education and healthcare.

By estimating the benchmarks that would need to be achieved at each stage of the population's growth, the team mapped the potential of any settlement on Mars eventually becoming entirely self-sufficient. For each growth stage, they identified the similarities and differences with historical and present-day human activity on Earth in terms of population, economy, society, and psychology. These included human spaceflight, historical shipping activities, Antarctic research bases and submarine crews.

04

Lessons from the Eco-City: A Manifesto for Governing Life on Mars

Dr. Robert Cowley
King's College London

This project used eco-city developments on Earth as a potential analog for Martian governance policy. Terrestrial eco-cities include a broad range of communities that seek to be smart, sustainable, and green. Examples include Dongtan eco-city, near Shanghai, as well as more radical experimental cities such as Arcosanti in the Arizona desert.

To develop a comparable policy framework, researchers organized a workshop that brought together political scientists, architects, and urban designers, as well as academics exploring the interface between science-fiction and technology, and the social and political implications of technology. The key findings and discussion points from the workshop were published in January 2019 as A Manifesto for Governing Life on Mars.

04

Space Settlement Governance: An Analysis of Legal and Policy Issues

Thomas Cheney
Centre for a Spacefaring Civilization

In this project, researchers studied existing space treaties, such as the 1967 Outer Space Treaty, to inform the development of a potential international legal framework governing space settlements. The team sought to incorporate lessons learned from historical, or analog, models comparable to space settlements, such as early North American settlements and Antarctic research bases.

The project also looked at the wider range of potential legal and policy issues that would arise once longer-term space settlements are established, including public-private partnerships, international, intranational, transnational, or supranational collaboration, and various ethical issues.

Optimal Mineral Procurement Contracts for Space Mining Missions

Ben Gilbert and Ian Lange
University of Washington

With economically viable space mining looming on the horizon, a team of researchers from the University of Washington developed potential contracts that could be used to facilitate private sector space mining, addressing the existing business uncertainty surrounding the practice. The project tackled the important issues the sector may face, such as the potential impact on mineral market prices should space mining become cost efficient and how to respond when the market price of minerals mined in space fluctuates during the time it takes to transport them to Earth.

Researchers looked at the types of contracting agreements between suppliers and buyers that will induce investment in space mining ventures when it is profitable to do so. They used economic models from game theory, industrial organization, and incentive contracting in to determine an existing minerals market equilibrium in terms of industry size, number of firms, quantities, prices, and profits. They also examined the shift in such equilibria under the potential entry into the market by new space mining firms, as well as the contract terms that are likely to produce stable prices versus terms that are likely to produce disagreement following the initiation of production.

05

Health, Robotics, and Communication

One of the biggest hurdles space research and exploration will need to overcome is the potential impact of the extraterrestrial environment on astronauts' and eventually space settlers' health. In addition to space radiation, people are likely to face a number of physical and psychological challenges to living in space.

Several of the funded projects look at the different technologies through which human health, communication, and interaction in space can be supported for safe long-term space missions.

05

Gesture-based Robot Control for Telemanipulation in Space Environments

Dr. Calogero Maria Oddo, Luca Massari, and Jessica D'Abbraccio
The BioRobotics Institute, Sant'Anna School of Advanced Studies

In this project, researchers contributed to the development of a technology that seeks to replicate the sense of touch, allowing engineers to physically "touch" objects remotely, known as "teleoperation." The project team designed a haptic manipulator that delivers the perception of touch vibration to the user's fingertips, allowing them to control machinery remotely. Optical sensors track human hand gestures through a glove to deliver tactile feedback to the user.

Such technology will be able to enhance users' perception capabilities in high-precision teleoperation activities, such as the fine control of mechanical tools, or in scenarios when remote tasks require both force and precision. It could also provide amputees with prosthetic limbs that allow them to regain the sense of touch. Researchers are already working to develop bionic fingers that allow users to feel fingertip sensations with an enhanced level of realism.

The sensory augmentation provided by this technology has great potential for numerous fields, including robotics for search and rescue.

Robots Made of Plants

Paolo Gallina
University of Trieste

Space settlements may have limited access to metals, particularly refined metals, so vegetable fibers could become a more suitable material for constructing future objects on Earth and Mars. A team of researchers from Italy's University of Trieste developed prototypes of robots with structures made from the fibers of cultivated plants.

While plant fibers are already used to make furniture and some small objects, they are not often used to build technological appliances and products. This project team combined plants with other high-performance materials to build robots.

These robots could serve many purposes, including as an automated, intelligent irrigation system that monitors water and nutrient supply of crops, which could in turn be processed into materials to build more robots.

05

Exploring Interplanetary Communications Through Virtual Reality

Adalberto L. Simeone
Katholieke Universiteit Leuven

Researchers from the Katholieke Universiteit Leuven in Belgium explored how virtual reality (VR) could be used for interplanetary communications. VR telepresence can provide a more immersive experience for people who are separated by great distances, as opposed to conventional audio and/or video communication.

The team found that the main challenge is the communication delay between two planetary bodies. While this delay is barely noticeable between the Moon and Earth (about 1.5 seconds), it jumps to between three and 20 minutes each way for Earth-Mars communications, and to four years each way between Earth and a hypothetical settlement in Alpha Centauri, the closest star and planetary system to our own.

The project used immersive VR to simulate various communication scenarios – Earth-Moon, Earth-Mars, Mars-Mars, and Earth-Alpha Centauri. In the study, participants played the role of future colonists and interacted with a "welcome for new arrivals" VR experience that introduced them to the idea of living on another planet.

Participants were then asked to communicate their experience back to Earth. Researchers collected both quantitative (time, movement data, VR interactions) and qualitative data (theme of the exchanges, user behavior, interviews, presence) in order to evaluate the effectiveness of VR communication compared to conventional methods.

05

Study of the Cognitive Effects of Astronauts' Exposure to High-energy, High-Z Particles

S.M.J. Mortazavi, S.M.T. Razavi Toosi, P. Roshan-Shomal, Seyed Alireze Mortazavi, A. Kaveh, and G. Mortazavi
Shiraz University of Medical Sciences,
Fox Chase Cancer Center

This research team conducted a neuropsychological assessment of people living in areas with various levels of Radium-226 (Ra-226) – a radioactive heavy metal that is produced as uranium decays – as a potential human analog for astronauts' exposure to space radiation.

Mitigating health risks arising from radiation exposure is critical for deep-space exploration. Astronauts could develop acute radiation syndrome, cancer, behavioral and cognitive impairments, and memory deficits caused by the exposure of their central nervous system to high levels of space radiation.[iv]

In this project, the team tested participants from some inhabited parts of Ramsar, a coastal city in Northern Iran, which has extraordinarily high natural levels of Ra-226 due to the presence of this radionuclide and the products of its decay, which are brought to the Earth's surface by hot springs. The project team estimated the mean effective Ra-226 dose participants were consuming through fruits and vegetables grown locally. They used multivariate analysis and multiple linear regression analysis to identify potential relationships between the cognitive status of the participants and Ra-226.

iv The importance of study of brain exposure to alpha particles emitted from sources such as radium is well documented now. "NASA is interested that radium, deposited in the brain, releases high-LET alpha particles - the only human analogue, though limited, for high energy, high-Z particles (galactic cosmic rays) traveling through space that might affect astronauts on Mars missions".

Investigation of the Transport of Biomass and Aerosols Through the Atmosphere in Mars Analogs

María-Paz Zorzano
Atmospheric Science Group, Luleå University of Technology

The study of life in the universe beyond Earth, known as "astrobiology," is a rapidly expanding field. This project team looked at astrobiology and the issues that could arise if life is discovered on, or migrates to, other planets. Among the issues that need to be considered, contamination is a critical area of research for space and health scientists. Microbes will inevitably be transported with humans to Mars, and it will be critical to understand how the Martian atmosphere will respond to the introduction of human life.

Presently, all space agencies adhere to the international protocols against "forward contamination," or inadvertently spreading Earth's germs to another planet or moon. This would ensure that subsequent explorers know if the presence of Earth bacteria was due to contamination, or if Earth's bacteria are naturally spread through the Solar System as suggested by the theory known as "panspermia."

The reverse problem is "backward contamination" – inadvertently returning to Earth carrying some extraterrestrial microbes. Humans would not have the natural antibodies or resistance to any possible illnesses these could cause. The project team noted that "the fate of entire Khoikhoi clans who were wiped out by smallpox infections, to which they had no natural resistance, is merely one historical example warning us."

The scientists working on this project estimated the potential risk of contamination of the Martian surface by humans. They investigated whether biomass and aerosols could be transported through the air in the Atacama Desert in Chile, one of the most arid environments on Earth.

Conclusion

The inaugural MBR Space Settlement Challenge realized a number of important objectives. The submitted projects generated new insights and strengthened and further developed existing knowledge, presenting important implications for space research. More critically, they hold many applications and opportunities in tackling challenges here on Earth.

The completion of the MBR Space Settlement Challenge also highlights the importance of taking a global approach to space exploration. The cooperation between international public and private sector partners is critical in order to contribute to space research and to address global geopolitical challenges such as climate change, food security, and water scarcity.

It has been suggested by some scientists that humans will eventually become a multi-planet civilization. Elon Musk, founder of SpaceX, has posited that this could happen as soon as in the next few decades. At the present stage, it is not yet clear how all the technological hurdles will be crossed. Nevertheless, the endeavor to ask the question is leading to the discovery and invention of our future here on Earth.

Cross-border investment and collaboration in space research and exploration is already growing visibly as both public and private sector entities are partnering with foreign agencies and, in some cases, rival companies, to access resources, talent, and funding. For example, the United States (US) and Russia have agreed to build a new space station following the retirement of the International Space Station in 2024.

In recent times, the steady growth of private sector players in the space industry, such as Virgin Galactic and SpaceX, is raising the question of whether the future of space research will be dominated by commercial companies. For example, in 2018, SpaceX launched the world's most powerful rocket, Falcon Heavy, replacing NASA's Saturn V, which had previously held the title.

Nevertheless, governments and the private sector both have important roles to play in space exploration as each holds particular advantages. While private companies often enjoy faster bureaucratic processes and can secure or reallocate funding relatively quickly, the impact of shareholder sentiment can increase volatility and limit companies to respond to short-term profitability pursuits. Longer-term goals, which might not be profitable in the short term, can be driven by public sector funding.

This relationship between the public and private sector is already visible in many instances, such as in NASA's contract with Boeing to transport astronauts to the International Space Station and SpaceX's agreement with the US Air Force to launch a space drone. The future of space exploration is likely to be characterized by the strengthening of this relationship.

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