

EXPONENTIAL TECHNOLOGY IMPACT REPORT

DRAFT

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Singularity
University

SPACE

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1 Scope of this Report

*The surface of the Earth
is the shore of the cosmic ocean
Recently we've waded a little way up
and the water seems inviting*

– Carl Sagan, “A Glorious Dawn”

Humanity is presently a one-planet species. Although we have sent humans into space, and even to the moon, they have only visited and then returned home to Earth. There are two ways in which this fundamentally limits us: First, it limits the resources available to us, in terms of both matter and energy. Second, it makes us vulnerable to total destruction as a species, should a catastrophe of planetary scale occur.

This report focuses on applications of exponential technologies that may facilitate the eventual establishment of a permanent human presence in space. These steps include the development of technologies to reduce the barriers to entry into space, technologies that may be needed to remain in space indefinitely (while also being useful on Earth), practical strategies to use resources which are off Earth, transformative changes in the business of space science and exploration, and means to educate, excite, and inspire the general public about the possibilities and importance of human space exploration.

1.1 Structure of this Report

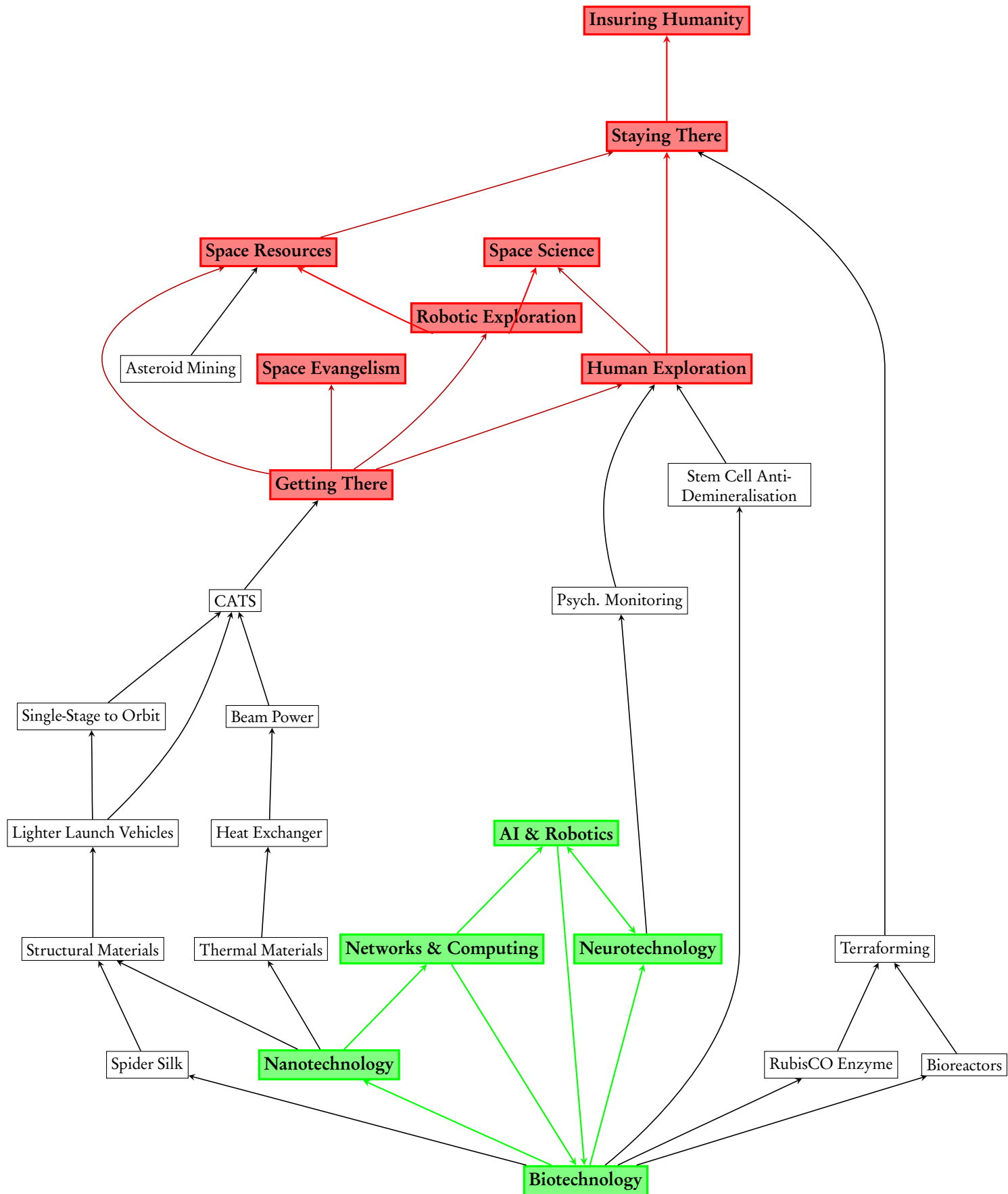
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1.1.1 Digraph

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2 State of the Problem Space

2.1 Overview

Doing business in space should be easy, but it isn't. It's hard to get into space, even sending robots rather than humans. It's hard to stay in space for very long—again, even if you send robots. It's hard to make use of the resources available in space. And it's hard to convince many people that going to space is even a good idea.

2.2 Aspects

We have chosen to focus on the following aspects of the problem space:

2.2.1 Getting There

2.2.2 Staying There

2.2.3 Human Exploration

2.2.4 Robotic Exploration

2.2.5 Space Resources

2.2.6 Space Science

2.2.7 Space Education/Evangelism

A key underlying problem to the limit of humanity's progress in space is that the majority of the human species is uninterested in space. Activities in space today do not inspire the awe that they once did: instead of watching astronauts walk upon the surface of a celestial body for the first time, today, if we're lucky, we get to watch them repair the toilet on the International Space Station. Educational outreach is a good start, but we need to connect humanity to space in a more natural way. Global warming is now perceived as a threat so compelling that most people believe we need to do something about it. But this threat is dwarfed by that of remaining on this planet indefinitely.

NASA's education program attempts to make space and the STEM (Science Technology Engineering and Math) curriculum exciting for students, but they do it without an understanding of the progress exponential technologies will have on the space industry. Students today rarely realize that when they grow older they will have a completely different tool set with which to tackle space. We should teach them what the world will be like in a decade or two and excite them on the possibilities they can create.

In all instances of educating the public on the importance of space, from youth to the elderly, opening the space frontier is never presented as an explicit need—which it is. Space is often considered to be primarily beneficial as an engine for creating technological spin-offs, but even if space exploration paid no technological dividends, it would still be crucially important. People don't appreciate the voyage of Christopher Columbus to the Americas primarily because of the new sextant developed for the journey that was eventually spun off to the private sector and used in merchant shipping.

It is human nature that we need to "see it to believe it," and maybe this is what is holding back humanity from understanding why space exploration is a necessity for survival. Until ordinary people can experience space through their own eyes, the possibilities that it holds will not be fully understood. What will happen when the first child can see our home from space, or when the first ballet dancer experiences weightlessness, or when a paraplegic is given mobility again? Let's not just tell humanity about space, let's give them access to space.

2.2.8 Insuring Humanity

2.3 Breakdown

- **Getting There/Transportation:** Cheap access to space is the single most important thing that could happen to drive space exploration and colonization
 - Earth to **Low Earth Orbit (LEO)**: Propulsion systems with higher thrust and **specific impulse (I_{sp})** are needed, **Single Stage to Orbit (SSTO)** vehicles would be ideal, and our current systems are largely non-reusable and made from materials that are highly suboptimal from a theoretical point of view.
 - **LEO** to Anywhere: Propulsion and braking systems with high I_{sp} and low thrust are needed, along with light structure spacecraft, formation flying, radiation shields, etc.
 - **Raw Materials:** As all tools and parts used in space are currently made on Earth, they must be made to high tolerances and sent on relatively low-acceleration launch vehicles to prevent damage; shipping raw materials would not have such problems.
 - **People:** Space travel is still far riskier than commercial aviation, and there are few mechanisms by which spacecraft can fail while keeping the crew alive.
- **Staying There**
 - **Research Labs:** Some research is not possible in the Earth's gravity.
 - **Permanent colonies**
 - * In **LEO**: Need reliable infrastructure and life support
 - * On the Moon: Desire robotics for automated resource extraction, construction and maintenance.
 - **Funding/business models:** Need a space-based economy that doesn't rely on Earth (complete **In-Situ Resource Utilization (ISRU)** for an entire society).
 - **Social and political structures:** Ensuring that citizens of space societies are safe and granted basic rights. Negotiations between space colonies and space↔Earth.
 - **Ownership:** How shall it be decided who owns portions of space, or resources brought back from space?
 - **Speciation/Human mutation:** Societies colonizing space for a long period of time will eventually become a different species from those on Earth. This raises many ethical and political issues.
 - **Communications:** Need a self-configuring, adaptive deep-space network, tied to the Internet.
 - **Universal timestamping:** To enable information exchange, we will need standard ways to timestamp data and standardize metrics for measurement.
 - **Resupply:** Need for a cheap launch system, cheap propulsion between the supply station and the colonies, and access to continual resources
 - **In-situ resource utilization:** extracting and using resources from planets, moons, and asteroids, for usage in construction, propulsion, power, sustenance for astronauts. Overall goal is to build systems that sustain, grow, and replicate without input from Earth.
 - **Terraforming**

- * Atmosphere: Need to develop an atmosphere with a balance similar to Earth's, allowing life to flourish (proper balance of nitrogen, oxygen, argon, and CO₂). Also need to maintain the atmosphere (example: having a magnetosphere on Mars).
- * Soil: Soil leads to plant life and the consistent production of food. Plant life will lead to an ecosystem on Mars and other celestial bodies that will help maintain the atmosphere and allow life to flourish.
- * Microbes: How might we synthetically engineer microbes for the purpose of sending them to remote planets and having them perform terraforming processes? To what extent do we need to be careful about introducing certain lifeforms to remote planets?

● Robotic Exploration

- Remote Controlled: Our current interfaces are insufficiently natural, lacking haptic feedback or immersive views, and deal poorly with low bandwidth and high latency.
- Semi-autonomous: The latest space technology lags far behind the state of the art in “narrow AI” or planning algorithms.
- Fully autonomous: Nearly all space missions today must be heavily monitored and guided from the ground.
- Communications: Our communications infrastructure in both near and deep space leaves much to be desired, and cannot support an exponentially growing quantity of space computing nodes.
- Better materials: Need materials that are stronger, lighter, and easy to develop/replicate. Weak materials fall apart in space's harsh environments, heavy materials increase transit time, and rare materials limit product line.

● Human Exploration

- **Closed-Loop Life Support Systems (CLLSS)**
 - * Food: Need for a way to generate a complete, well rounded diet with minimal input and output - ideally 100% closed loop.
 - * Water: Need for sophisticated waste and grey-water systems for closed-loop water usage.
 - * Waste: Design waste out from the beginning - systems should operate in completely closed loops for matter and energy.
 - * Air: Assure fully closed-loop air systems able to work indefinitely at extreme reliability.
- **Human Health:** Issues include psychological health, crew selection, training, habitability and human factors requirements, social governance supports, infrastructures for long duration spaceflight, consent and justice for one-way missions, and strategies for permanent colonisation with ethical micro- and meso-social structures.
 - * Radiation Shielding
 - Need to establish acceptable radiation exposure limits
 - Need for formal alert/warning and communications infrastructure from pre-screening to initial construction to settlement.
 - Need mechanical counter-pressure and electrostatically charging materials for suit design.
 - Need to analyze long-term health risks.

- * Extreme habitat design: Need for human-rated and “homey” design, including spaces for privacy and socialisation, localized vehicles, sick bays, architecture with built-in physical countermeasures, teleconferencing/VR, hydrotherapy, color and light, and views of Earth, if possible. Also, new materials technologies are desirable, including:
 - inflatables
 - demountables
 - transformers
 - smart materials
- * Psychological well-being: Space radiation poses poorly understood risks to the central nervous system. Besides the late effects of long term radiation exposure, stress, deprivation, isolation, and confinement constitute major risks for the physical and mental health of space explorers during the missions.
- * Pharmacological support: treating space-related osteoporosis, cardiovascular problems, vitamin and nutrient loss, sleep disturbance, muscle atrophy, and cellular damage

- **Using Space Resources**

- **Energy Harvesting and Beaming:** Need a way to harvest resources and energy from the massive array of sources available in space. Asteroids and solar are likely the two most impactful. As far as beaming goes, a system is needed to transmit the energy from space to the ground. In the case of asteroids, transport of physical resources is needed.
- **Asteroid Mining:** Need a cost-effective way to reach near-earth asteroids, and a means to map, identify and choose which to go to. Also, desire automated mining techniques, self-replicating robots for networked mining swarms, mesh networks, autonomous behavior, and 3D printing for tool generation and maintenance
- **Political Challenges**
 - * Security restrictions such as [International Traffic in Arms Regulations \(ITAR\)](#): Need a framework for international cooperation in the private sector
 - * Space treaties: Need [Committee on Space Research \(COSPAR\)](#) regulations - sample return restrictions and planetary protection guidelines. There is some international disagreement.
 - * Fueling: Need for an international agreement that takes into consideration peaceful use, human safety, and waste mechanisms related to the extraction and utilization of fuel and nuclear energy
 - * Real Estate: No state has a claim to land rights in space; can private entities?
 - * Public/private partnerships: Need to exploit the full potential of spin-in and spin-off technologies. Space is more closed than other sectors. There are also underdeveloped marketing opportunities.

- **Education/Space Evangelism:** We need to enable the world to learn about space in awe-inspiring new ways. Most people don’t want to be “taught,” so the focus of the education problem is fostering excitement, enabling people to learn on their own, and showing people that we’re all connected to space.

2.4 Exponential Technology Areas

In this report, we will illustrate a number of opportunities to address the above problems with exponential technologies. This section serves as a brief overview to each of the exponential technology areas.

2.4.1 AI and Robotics

In the broadest sense, the fields of AI and robotics strive to make non-human systems able to perform human tasks, or other difficult tasks that are helpful to humans. Robotics focuses on the necessary physical capabilities, while AI focuses on the necessary mental capabilities. At present, AI systems are capable of solving a plethora of individual problems, each of them far more swiftly and accurately than a human could; but no robot is capable of loading a dishwasher yet. This phenomenon is represented by the term "narrow AI": each AI system today is typically helpless outside the situation it was designed for. These systems solve problems such as searching the Internet, routing FedEx packages, military logistics, or playing chess. However, it has been predicted that in the future, we will develop what is known as "strong AI": an AI system that nears human levels of tolerating uncertainty, and can generate original solutions to problems hitherto unseen and unanticipated by the designers of the AI.

2.4.2 Biotechnology

2.4.3 Nanotechnology and Materials Science

2.4.4 Information Technology and Networking

2.4.5 Neurotechnology and Medicine

2.4.6 Policy, Law, and Ethics

We are not in a position to fully analyze the far-reaching consequences of near-term steps by space agencies and private space entrepreneurs, however we can set about to establish a context for critical evaluation of our motivations and hesitations at the Singularity University during the 2010 GSP. This is a time to develop a culture of intense questioning and reflexivity, weighing up the pros and cons of social and education value, economic and political drivers, scientific benefits, risks, the battle for sovereignty between nation states; time readiness, and the lessons learnt from past human endeavors at each stage of mission planning and undertaking. Particular attention must be paid to our obligations and restrictions, the differences of moral standing and the agents behind them; the intrinsic and instrumental values of global peoples and the core truths of our calling, in order to plan effectively and to garner new insights and knowledge for wider reaching solutions to terrestrial concerns so that we can leverage exponentially advancing technologies for the benefit of humanity, the planet and the future of our activities in space. We have a responsibility to boldly stay to serve legitimate interests as a peaceful, well-meaning people and the opportunity to explore new ways of seeing life, and space, from a whole new perspective.

It is posited that if we are to actually improve standards of living on Earth through space by generating economic opportunity; providing access to new resources (material, intellectual and so on) then we need to bring about the prospect of rapid technological development, the cross-fertilization of ideas, new visions and shared dreams for the benefit of all human-kind and this begins with the power of the questions we ask ourselves, and the declarations we make for our future generations.

2.4.7 Entrepreneurship

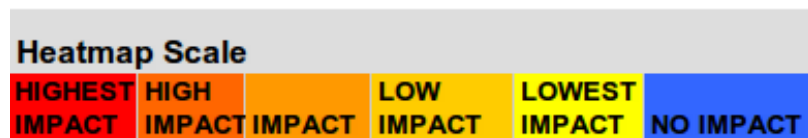
2.5 Classification of opportunities

We offer a brief taxonomy of the problems that exponential technologies need to help overcome during the next three decades in order to facilitate the exploration and colonization of space. For each area in this taxonomy, we explore the role that each exponential technology might play.

1. AI and Robotics
2. Biotechnology
3. Nanotechnology and Material Sciences
4. Information Technology and Networking
5. Neurotechnology and Medicine
6. Policy, Law and Ethics
7. Entrepreneurship

The goal of these definitions is twofold: to map for future reference our current understanding of the relative role of each of the exponential technologies and solution domains, and to help us focus our in-depth analysis of conceptual solutions to those areas that appear more fruitful.

We have divided the problem space in two different ways, which we call *heatmaps* and *roadmaps*. First, we have intersected each of the problem areas in section 2.2 with each of the exponential technologies in the above outline. Second, we have focused on 30-year roadmaps for each exponential technology, and intersected the roadmaps with aspects of the space exploration problem. (Unfortunately, the latter roadmaps are in a form that is not easily converted to the printed page; a later version of this report will contain a visualization of these roadmaps.) The qualitative analysis of the relative importance of each of the solution domains is presented in the form of a series of *heatmaps*, according to the following scale:



	AI / Robotics	Biotech	Nanotech	Info / Networks	Neuro / Med	Policy / Law / Ethics	Entrepreneurship
Getting there							
<i>Transportation</i>							
Earth to LEO							
LEO to anywhere							
Raw Materials							
People							
	AI / Robotics	Biotech	Nanotech	Info / Networks	Neuro / Med	Policy / Law / Ethics	Entrepreneurship
Staying there							
Research Labs							
Mining / Work facilities							
Permanent Colonies in LEO							
Permanent Colonies in Luna							
Permanent Asteroid Colonies							
Funding / Business models							
Social and political structures							
Governance							
Ownership							
Speciation / Mutations							
Communications							
Universal timestamping and standards							
Resupply							
ISRU							
<i>Terraforming</i>							
Atmosphere							
Soil							
Microbial life introduction							
Mining							
	AI / Robotics	Biotech	Nanotech	Info / Networks	Neuro / Med	Policy / Law / Ethics	Entrepreneurship
Robotic Exploration							
Remote Controlled							
Semi-Autonomous							
Fully autonomous .							
Communications							
Better materials							

	AI / Robotics	Biotech	Nanotech	Info / Networks	Neuro / Med	Policy / Law / Ethics	Entrepreneurship
Human Exploration							
<i>Bio-Regenerative Closed loop life support systems</i>							
Food							
Water							
Waste							
Air							
<i>Human Health</i>							
Radiation Shielding							
Extreme habitat design							
Psychological well being							
Pharmacological support							
<i>Political and Cultural Challenges</i>							
International collaboration and public/private partnerships							
	AI / Robotics	Biotech	Nanotech	Info / Networks	Neuro / Med	Policy / Law / Ethics	Entrepreneurship
Using Space Resources							
Energy harvesting and beaming							
Asteroid Mining							
ITAR policy restrictions							
Space treaties							
Fueling							
Real Estate							
Cross Contamination							
	AI / Robotics	Biotech	Nanotech	Info / Networks	Neuro / Med	Policy / Law / Ethics	Entrepreneurship
Education							
Education							

3 Exponential Technology Opportunities

...For each of the sections below, we discuss the current state of the art, related exponential technologies, potential benefits, convergences with other technologies, and potential barriers to adoption.

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3.1 3D Printing in Space

Tools and parts for space exploration must be comprehensive, redundant, and able to withstand the forces of launch. As a result, they are bulky and inconvenient, and despite this, situations still occur in space when the right tool for the job is simply not available. New 3D printing technologies can change that. The future lies with fast, customizable manufacturing, with which tools and parts can be built on-demand in space.

3.1.1 State of the Art

Today's 3D printers here on Earth can fabricate objects made of some metals, ceramics, and plastics, and the palette of materials is expanding exponentially. There is even one 3D printer currently in production which can print objects made of more than one material. However, most current 3D printing mechanisms will not work in microgravity environments. For example, Selective Laser Sintering (SLS) uses a laser to selectively fuse together particles of build material (be it metal, ceramic, or plastic), building up the object layer-by-layer by a process of powder deposition. Without gravity, such deposition is impossible. A new technique called Electron Beam Freeform Fabrication (EBFF) [74] pioneered at NASA Langley overcomes this challenge by extruding metal directly from a tip. This is a promising technology, but is currently too heavy and low-resolution to be practically useful in space. However, these are merely problems of engineering that will improve with the exponential increase in the strength of materials.

3.1.2 Related Exponential Technologies

- Networks and computing systems enable the digital shipment of high-resolution part files
- AI can automate the process of designing a tool or choosing a tool design, given information such as a 3D scan of a machine to be repaired
- Nanotechnology will result in more precise fabrication processes, less waste of materials, and more easily reusable materials (i.e. nanodisassembler)

3.1.3 Potential Benefits

In the near term, the greatest use of 3D printing in human space missions is printing tools or components as they are needed. Custom-built tools mean fewer tools taken to orbit with less redundancy in number of tools taken. In the longer term, 3D printers are compelling and enabling tools for human colonization. The ability of either robots or humans to be able to print what is necessary using local materials is a compelling reason to pursue this technology.

3.1.4 Convergences

«to be completed»

3.1.5 Barriers

«to be completed»

3.2 Asteroid Mining

There are not enough raw materials present on planet Earth to sustain even today's level of technological growth for the next 20 years[23]. Perhaps even more astonishingly, there are not even enough raw materials on the planet for the world's current population to live with the quality of life of the modern developed world[40]. Thankfully, while these raw materials are scarce on Earth, they are highly abundant in the numerous near-Earth asteroids and comets that circulate our solar system. Hence, it is of great importance that a powerful initiative be put in to place to secure the valuable materials from these bodies and bring them back to Earth.

3.2.1 State of the Art

«to be completed»

3.2.2 Related Exponential Technologies

- As artificial intelligence and computing increase exponentially in power, the degree of autonomy that is available for robotic mining of remote asteroids will grow powerfully, enabling cheaper and more successful missions
- Advances in biotechnology will enable us to engineer synthetic organisms that extract and refine materials from asteroids cheaply and reliably
- As our networks and communications systems become more capable, so will our ability to communicate with remote mining systems and colonies
- The availability of nano-satellites will enable cheap, small, and highly redundant mining missions to numerous asteroids in our solar system

3.2.3 Potential Benefits

Mining the asteroids will not only avert the global crisis that would have been brought about by a poverty of critical resources, it will usher in a new era of utopian abundance in the near-term future of humankind.

3.2.4 Convergences

«to be completed»

3.2.5 Barriers

The successful return of asteroidal resources to Earth presents a number of deep challenges. It is quite likely that such a success would be preceded by a series of unsuccessful attempts, rendering the ultimate success prohibitively expensive. In this section, we *«will»* describe a set of paradigm-shifting asteroid mining methods that are made possible by the great wealth of powerful exponentially growing technologies that will be available in the next 10 to 20 years.

3.3 Beam Power

3.3.1 State of the Art

Since the first rocket launch, the cost of launching objects into space has never dropped exponentially. This has been a major impediment to the advancement of the space industry, and many exponential industries such as the computing industry have left it behind in the dust. Perhaps the most promising way to turn space launch into a technology that decreases in price exponentially is external propulsion. In such a system, instead of carrying both fuel and propellant onboard the launch vehicle, the energy to exhaust the propellant is provided from outside the vehicle, for instance via a microwave beam, and transduced into thrust by a heat exchange engine. An externally powered space launch system represents a completely new paradigm of space access as it transfers all of the expensive and heavy components associated with the space launch to the ground facility and opens an opportunity for the design of highly efficient and cheap launch vehicles. Once the ground facility is established, the cost of space launch can be reduced essentially to the cost of associated resources, such as energy delivered from the ground and hydrogen propellant.

3.3.2 Related Exponential Technologies

The microwave system will decrease in price as the price per megawatt decreases over time. This price will decrease over time as the maximum power output of each individual [gyrotron](#) increases over time, and the cost of each gyrotron decreases over time. The maximum power output of each individual gyrotron will increase over time as superconductor performance increases and as computing power increases, insofar as computing power influences the control dynamical systems in the gyrotron. Gyrotrons will get cheaper as the 3D printing of materials gets cheaper over time and 3D printing technology increases in capability. Also, the gyrotron cost will decrease as superconductors get cheaper and more effective. The materials required for the diamond window component will also decrease over time. Control dynamical systems will become cheaper as computing power gets cheaper and also as 3D printing gets cheaper and more effective.

The heat exchange engine will get cheaper as the turbopump gets cheaper, which will primarily be driven by 3D printing getting cheaper and more effective. The hydrogen tank component of the heat exchange engine will get cheaper as the manufacturing of nanocomposite materials becomes more effective. This will be driven precisely by the decrease in the mass of the tank and the decrease in the price of the tank, while the volume and strength of the tank are held constant. The heat exchanger component of the engine will become cheaper as the manufacturing of nanocomposite materials becomes more effective and cheaper over time.

The launch vehicle itself will become cheaper as well as the manufacturing of nanocomposites becomes more effective and cheaper, and as the mass of the launch vehicle decreases while the strength of its structure remains constant over time.

Finally, preflight testing and design will become cheaper as computer-aided design becomes more effective and cheaper, which will happen as computing power becomes more powerful and cheaper, and as CAD algorithms improve. Preflight testing and design will also become cheaper as multiphysics simulations become more powerful. This will be a result of software functionality improving, hardware functionality improving, crowd-sourcing more prevalent, and regulation becoming more slack on the levels to which technology must be tested.

3.3.3 Potential Benefits

The microwave beam-powered launch system will decrease in price exponentially as a result of four of its components decreasing in price exponentially. In addition, we expect the following benefits:

1. Single Stage to Orbit with an increased safety factor and full reusability
2. 5–10 times more payload into orbit than a chemical rocket of the same initial mass
3. One type of propellant, no chemical reactions on board
4. Much simpler, highly modular launch vehicle with cheaper construction and maintenance

3.3.4 Convergences

«to be completed»

3.3.5 Barriers

«to be completed»

3.4 Biology-Based Life Support Systems

3.4.1 State of the Art

Identifying mineral biomarkers used for the search for life in space. Discovery of microbial habitability in air (Green 2010) [78].

3.4.2 Related Exponential Technologies

Harnessing the interactions of Microorganisms with geological, biological and technological substances for the advancement of life support systems in extreme environments.

3.4.3 Potential Benefits

- *10 years* – Continued search for life across the universe via microbe-mineral interactions (leveraged by microSAT and emergent bioSAT technologies); and development of sophisticated life support systems integrations such that microbe-mineral interaction with the bio-tech interface
- *20 years* – Extraction of useful minerals from space-based resources; and the refinement of closed-loop life support systems (CLLSS) with microbe-mineral interactions leads to higher order organization of the whole system which now functions as bio-regenerative and adaptive system able to switch between closed-loop capabilities and environmental interactions for in-situ resource utilization where advantageous.
- *30 years* – Controlled amelioration of regolith and symbiotic advanced life support systems for human life in extreme environments.

3.4.4 Convergences

«to be completed»

3.4.5 Barriers

«to be completed»

3.5 Cloud of Satellites

3.5.1 State of the Art

«to be completed»

3.5.2 Related Exponential Technologies

Advances in processor density and computing power miniaturization, ad-hoc networking protocols, content addressing and routing, new materials, micro and pico-propulsion, small energy harvesting techniques, artificial-intelligence assisted scheduling, relative positioning systems and formation flying, all these trends will converge in the rapid surge of a distributed infrastructure built from mass-produced, cheaply replaceable units that, working collaboratively as a swarm, will offer higher resilience and far more advanced capabilities to a wider set of actors.

3.5.3 Potential Benefits

Satellites will become our shared, space-based sensor and communications networks to support Earth services, as well as the commercial exploitation, research, exploration and colonization of the solar system. From our big “mainframe” satellites of today, to an ubiquitous service-based infrastructure of femtosatellites and smart dust.

3.5.4 Convergences

«to be completed»

3.5.5 Barriers

«to be completed»

3.6 Disease Treatment in Space

The environment of space provides a unique platform for creating treatments for diseases on Earth, and also a new set of challenges for treating astronauts and space colonists. Building a research platform in space is necessary to transfer all the benefits provided by its unique environment in the form of enhanced information back to Earth.

3.6.1 State of the Art

The already existing ISS platform could be used in combination with Nanoracks and CubeLab infrastructure already being booked for imminent launch.

3.6.2 Related Exponential Technologies

Biotechnology

«to be completed»

3.6.3 Potential Benefits

Microgravity provides an opportunity to disrupt normal processes of gene expression and biochemistry. Some preliminary work has shown that second generation drosophila flies have reduced tumor growth when first and second generation flies have grown in a microgravity environment. Faster and better techniques such as gene sequencing technology enables us to iterate such experiments faster, and probe the reason for such results exponentially faster and better. Protein crystallography may also be enhanced by the absence of gravity, thus providing much better quality crystals that could be imaged by X ray crystallography. These images could then be used on Earth for drug targeting and development. By understanding these processes we may be able to improve the knowledge of cancer and other diseases, and possible cures. More studies in the effects of microgravity in cancer and other diseases, especially on the organism level are needed, and will be enabled by such recent technologies as cheap commercial launches and modular experiment systems (e.g. Nanoracks).

Microgravity provides a novel opportunity to do organ development and embryogenesis. There are new techniques in organ printing and 3D bioreactors that may benefit from the microgravity environment. 3D bioreactors can grow cells on an artificial 3D matrix.

3.6.4 Convergences

«to be completed»

3.6.5 Barriers

«to be completed»

3.7 Extreme Design: Inflatable architectures

In this ever-changing political climate, concepts of operation and mission design for future human activities in space environments have provided an opportunity for renewed consideration of requirement definition and validation, operation concepts definition and the processes for the validation and alternative mission architectures.

3.7.1 State of the Art

NASA completed and tested a surface Habitation demonstration unit (HDU) Pressurized Excursion Module (HDU-PEM laboratory) in 2010 to support a crew of 4 for a minimum of 14 days–60 days. Following this success, the eXploration Habitat (X-Hab) Academic Innovation Challenge as solicited by NASA HQ Exploration Systems Mission Directorate, Directorate Integration Office and Innovative Partnership Program Office The Habitat Demonstration Unit Project announced a challenge to design and demonstrate attachable inflatable technologies for the construction of a habitable loft (2nd level attachable) with self-deployable units to install to the standard interface on NASA’s hard shell Lab HDU-PEM. See: <http://www.spacegrant.org/xhab/>

3.7.2 Related Exponential Technologies

We will approach this challenge using innovative and experimental design incorporating the interdisciplinary spectrum of advancing technologies and strategies prevalent today and proposed for the future including biotechnology, design and living architecture, the arts, entertainment and communications sector, robotics and AI and material and space sciences.

3.7.3 Potential Benefits

«to be completed»

3.7.4 Convergences

Spin-off and spin-in potential technologies will be amplified and advanced where possible to transfer to Earth-based solutions to one of the world’s grand challenges to adequately shelter, shield, comfort and sustain human life. Furthermore, the team will design an educational outreach plan, leveraging opportunities for future business and research, whilst actively approaching the development of a successful research and design proposal for forthcoming manufacture and testing of innovative and advanced space, or Singularity-space hardware.

3.7.5 Barriers

«to be completed»

3.8 Nanomaterials in Satellites

We can use nanotechnology to protect satellites from radiation, both from space and from ground based technologies.

3.8.1 State of the Art

Purified metal single-walled nanotubes exhibit reflective properties, which may be useful on the exterior of space crafts. It would also be advantageous to disperse the radiation along the surface using nanotech. Carbon nanotube membranes (Buckypaper) could be useful in reducing electromagnetic events on the space craft. There are two ways they are built: directionally aligned, and randomly aligned, with thermal conductivities of 117 W/m*K and 56 W/m*K respectively. Northrop Grumman has demonstrated Nickel Nanostrands as an electromagnetic shield for satellites.

3.8.2 Related Exponential Technologies

Nanotechnology

3.8.3 Potential Benefits

By leveraging the properties of nanoscale gold to “squeeze” into tiny holes in the surface of a device researchers have doubled the detectivity of infrared detectors. Essentially this technology will enable ultra powerful and ultra small space craft imaging.

3.8.4 Convergences

«to be completed»

3.8.5 Barriers

«to be completed»

3.9 Neuroscience in Space

Psychological health is critical to space explorers.

3.9.1 State of the Art

The current brain machine interface (BMI) technologies allow us to interact with our brains in both ways even when we are moving around. Real-time neural signals can be obtained noninvasively through lower resolution techniques such as EEG or invasively through implanted multielectrode arrays (MEA) which offer multiple site recordings with high temporal and spatial resolutions. Stimulations can be also applied to selective regions of the brain noninvasively through transcranial magnetic stimulation (TMS) or invasively with electrical stimulation through MEA. Both methods influence clusters of neurons while MEA offers stimulations with a better precision.

Noninvasive neural recordings can help us understand the conditions of individual physical and psychological health [28]. Utilizing the real-time noninvasive neural signals recorded, neurofeedback helped the subjects to learn how to control over their own brain activation [28]. Success can be also found in the treatment of attention deficit disorder, pain control and reduction in anxiety.

Researchers have already demonstrated that we can control computer cursors and even robotic arms by decoding neural signals, such as the DEKA arm. Brain waves were also demonstrated to be able to classify a subset of words in internal speech [72].

3.9.2 Related Exponential Technologies

Neuroscience

«to be completed»

3.9.3 Potential Benefits

Various conditions are currently treated successfully with repetitive TMS, such as stroke, Parkinson's disease, depression, dystonia, tinnitus, epilepsy, amyotrophic lateral sclerosis, schizophrenia, addiction, obsessive-compulsive disorder, Tourette's syndrome, and memory dysfunction [67]. With improving selectivity, noninvasive neural stimulations are promising to provide easier treatments to various neural diseases. Besides health diagnosis, these signals can be also acting as lie detector which can prevent potential interpersonal misunderstanding and can be used an optimal conflict resolution tool in space. As the noninvasive recording techniques increase in their time and spatial resolution, real-time decoding of the resulting neural signals will help us to handle multiple tasks and communicate with multiple colleagues more efficiently.

3.9.4 Convergences

«to be completed»

3.9.5 Barriers

«to be completed»

3.10 Planetary Protection

3.10.1 State of the Art

Various levels of planetary protection, sample return restrictions and cross-contamination considerations including the issue of material selection for space components and assembly, protocols and handling.

3.10.2 Related Exponential Technologies

«to be completed»

3.10.3 Potential Benefits

- 10 years – Establishment of an International Planetary Protection Working Group liaising with a Life and Physical Advisory Group to define planetary protection guidelines, evaluate the legal and ethical considerations and assess biological cleanliness and readiness of space hardware. Greater international consultation, information exchange, and standardisation.
- 20 years – Development of active biological space debris identification and disposal. Processes to attend to mutant life forms, hybrid life forms, bio-machina cyborgs and the semi-living. Fractionated spacecraft. Preparedness and response technologies and protocols for Bio-in-space disasters.
- 30 years – Preparedness and response technologies and protocols for Bio-in-space disasters. Inter-planetary and localized organic Governance, Peaceful Purpose of Space Treaty revised and upheld, Space and Security a major-Earth based priority

3.10.4 Convergences

«to be completed»

3.10.5 Barriers

«to be completed»

3.11 Swarm Space Exploration

3.11.1 State of the Art

Robotic space exploration is rare, expensive, and bulky. The root cause is due to a cycle of problems that build up on one another, driving up the cost and complexity of space exploration missions.

- Problem 1: Launch cost. The cost of getting into space immediately subdues a robotic space mission to be tens of millions, if not hundreds of millions, of dollars just for the launch.
- Problem 2: Complexity. Due to the high cost of launch, spacecraft and space probes are “built to last” as a high rate of failure would mean the waste of the millions of dollars spent on launch. This leads to spacecraft that are heavier, bulkier and more complex.
- Problem 3: Development time. Due to being built to last and the increased complexity, the spacecraft is designed over a series of long, laborious processes in an effort to increase mission success.

The cycle continues: Due to the high amount of time and labor costs being spent on a mission, NASA wants to get more “bang for its buck,” and adds more features to its spacecraft and space probes. This increases the weight, which increases the launch cost, which increases the complexity, which again increases the time. It’s a vicious cycle that we believe can be broken with small spacecraft and space probes that are easily expendable.

3.11.2 Related Exponential Technologies

As sensors, computation, and communications technology gets faster, smaller, and cheaper, a new paradigm of space exploration becomes possible. Swarms of small spacecraft with cameras, magnetometers, or other sensors could be deployed for a wide array of modular missions. Hundreds to thousands of these small spacecraft would be designed to be cheap enough and numerous enough that the loss of multiple scouts due to technical failures or radiation damage would not hinder the larger mission objectives.

The importance of exponentially advancing technologies in miniaturization of scout components is clear. For example, if ultra-high resolution cameras are not necessary, we can take advantage of the cellphone industry's drive to entire cameras that are $< 1\text{cm}^3$ and still getting smaller. Magnetometers used to be bulky devices but we are continually getting smaller and more accurate (SQUID magnetometers for instance were invented in the 1960's but are still becoming better engineered and more mainstream). Moore's Law predicts further miniaturization of computational power, and communications technology can be miniaturized further and driven to lower power if the scouts are each communicating not back to Earth but to each other, perhaps with a large mother scout to beam the information back to Earth for missions far from Earth.

3.11.3 Potential Benefits

The applications of these small spacecraft are manifold, for example:

- Swarm satellites: Swarms of small inter-communicating satellites surrounding the earth, monitoring natural processes such as global warming or tsunamis, through their own miniaturized sensors or by GNSS reflectometry, or used for earth communication and human/object monitoring.
- Detect solar wind disruption to communications systems before it hits on earth: the solar wind is comprised of charged particles that travel slower than light. We can sometimes predict increases in solar wind activity from earth, minutes before it happens, by monitoring flares from the sun. However we can only guess at the magnitude of the solar wind for a given solar flare event. Small scouts nearer the sun could detect increases in solar wind, which would be correlated with observation of solar flares from earth, to provide better knowledge of the magnitude of solar wind disruptions to earth-based communication systems.
- Exploration for universities, research organizations, small groups, and eventually everyone: Many small scouts with cameras and attitude control could be sent to moons, planets, asteroids, and comets, where they could be controlled on a timeshared basis by the small research groups to study the many unexplored parts of our solar system. Eventually, with enough small spacecraft, this could be a way to involve and excite the general public about space exploration, and could also be used as a revenue model if we charged for the time spent controlling the satellite and taking pictures, or charged the citizen explorers to name certain minor bodies or unnamed geological features that they discover, and have these names officially recognized by the IAU. The public could also take pictures of the Earth from near or far (your own "pale blue dot" picture) which would emphasize in the general public's mind the importance of preserving our precious Earth.
- Countless small scouts could find new asteroids, potentially identifying Earth-crossing asteroids.
- Small scouts will be useful in asteroid and resource prospecting. There are huge numbers of asteroids to choose from and the first few asteroids we mine will have to be carefully selected. Small scouts sent to many different asteroids will allow us to screen potentially thousands of asteroids quickly to determine their composition. In one approach, one small scout would slam into the surface of an asteroid while the other one monitors the ejecta or even captures some ejecta and returns it to Earth or a space base for analysis.

3.11.4 Convergences

«to be completed»

3.11.5 Barriers

«to be completed»

References

- [1] Neuritogenesis: A model for space radiation effects on the central nervous system. *Advances in Space Research*, 14:467–474, 1994. (Not cited.)
- [2] Spinoff. *Transportation*, 2006. (Not cited.)
- [3] Gyrotrons, 2010. URL <http://www.cpii.com/product.cfm/1/18>. (Not cited.)
- [4] Synchronized Position Hold Engage and Reorient Experimental Satellites, 2010. URL <http://ssl.mit.edu/spheres/>. (Not cited.)
- [5] Techsat 21 Project Pages, 2010. URL http://ssl.mit.edu/overview/OpenHouse2001/DSS/OpenHouse2001_DSS.pdf. (Not cited.)
- [6] Long Duration Psychology, 2010. URL <http://history.nasa.gov/SP-4225/long-duration/long.htm>. (Not cited.)
- [7] NASA's Science Mission Directorate (SMD) Education and Public Outreach program, 2010. URL <http://teachspacescience.org/cgi-bin/ssrtop.plex>. (Not cited.)
- [8] Outreach to Space, 2010. URL <http://www.outreachtospace.org/>. (Not cited.)
- [9] SEi Announcements, 2010. URL <http://www.spaceed.org/>. (Not cited.)
- [10] New Nanotech Discovery Could Lead To Breakthrough In Infrared Satellite Imaging, 2010. URL http://www.spacemart.com/reports/New_Nanotech_Discovery_Could_Lead%_To_Breakthrough_In_Infrared_Satellite_Imaging_999.html. (Not cited.)
- [11] M. Avnet. The space elevator in the context of current space exploration policy. *Space Policy*, 22(2):133–139, May 2006. ISSN 02659646. doi: 10.1016/j.spacepol.2006.02.005. URL <http://linkinghub.elsevier.com/retrieve/pii/S026596460600021X>. (Not cited.)
- [12] S. D. Baum. Cost-benefit analysis of space exploration: Some ethical considerations. *Space Policy*, 25(2):75–80, May 2009. ISSN 02659646. doi: 10.1016/j.spacepol.2009.02.008. URL <http://linkinghub.elsevier.com/retrieve/pii/S0265964609000198>. (Not cited.)
- [13] I. Bekey. Extremely Large Swarm Array of Picosats for Microwave/RF Earth Sensing, Radiometry and Mapping, 2005. (Not cited.)
- [14] Benguría A, Grande E, de Juan E, Ugalde C, Miquel J, Garesse R, and Marco R. Microgravity effects on *Drosophila melanogaster* behavior and aging: Implications of the IML-2 experiment. *Journal of Biotechnology*, 47 (2-3):191–201, 1996. URL <http://www.ncbi.nlm.nih.gov/pubmed/8987567>. (Not cited.)
- [15] L. Billings. Exploration for the masses? Or joyrides for the ultra-rich? Prospects for space tourism. *Space Policy*, 22(3):162–164, Aug. 2006. ISSN 02659646. doi: 10.1016/j.spacepol.2006.05.001. URL <http://linkinghub.elsevier.com/retrieve/pii/S0265964606000440>. (Not cited.)
- [16] R. Birk. Government programs for research and operational uses of commercial remote sensing data. *Remote Sensing of Environment*, 88(1-2):3–16, Nov. 2003. ISSN 00344257. doi: 10.1016/j.rse.2003.07.007. URL <http://linkinghub.elsevier.com/retrieve/pii/S003442570300227X>. (Not cited.)
- [17] J. Blamont. International space exploration: Cooperative or competitive? *Space Policy*, 21(2):89–92, May 2005. ISSN 02659646. doi: 10.1016/j.spacepol.2005.03.003. URL <http://linkinghub.elsevier.com/retrieve/pii/S0265964605000238>. (Not cited.)
- [18] D. Broniatowski and A. Weigel. Articulating the space exploration policy–technology feedback cycle. *Acta*

- Astronautica*, 63(5-6):649–656, Sept. 2008. ISSN 00945765. doi: 10.1016/j.actaastro.2008.04.006. URL <http://linkinghub.elsevier.com/retrieve/pii/S0094576508001495>. (Not cited.)
- [19] W. Carter. Significant results from using earth observation satellites for mineral and energy resource exploration. *Advances in Space Research*, 1(10):261–269, 1981. ISSN 02731177. doi: 10.1016/0273-1177(81)90402-6. URL <http://linkinghub.elsevier.com/retrieve/pii/0273117781904026>. (Not cited.)
- [20] C.-C. Chang, Y. D. Sharma, Y.-S. Kim, J. A. Bur, R. V. Shenoi, S. Krishna, D. Huang, and S.-Y. Lin. A Surface Plasmon Enhanced Infrared Photodetector Based on InAs Quantum Dots. *Nano Letters*, 10(5):1704–1709, 2010. URL <http://pubs.acs.org/doi/abs/10.1021/nl100081j>. (Not cited.)
- [21] S. Chung, P. Ehrenfreund, J. Rummel, and N. Peter. Synergies of Earth science and space exploration. *Advances in Space Research*, 45(1):155–168, Jan. 2010. ISSN 02731177. doi: 10.1016/j.asr.2009.10.025. URL <http://linkinghub.elsevier.com/retrieve/pii/S0273117709006887>. (Not cited.)
- [22] C. Cockell. Fostering links between environmental and space exploration: the Earth and Space Foundation. *Space Policy*, 18(4):301–306, Nov. 2002. ISSN 02659646. doi: 10.1016/S0265-9646(02)00043-7. URL <http://linkinghub.elsevier.com/retrieve/pii/S0265964602000437>. (Not cited.)
- [23] D. Cohen. Earth’s natural wealth: an audit, 2007. URL <http://environment.newscientist.com/channel/earth/mg19426051.200-earth-s-natural-wealth-an-audit.html>. (Cited on page 15.)
- [24] L. Cooper. Encouraging space exploration through a new application of space property rights. *Space Policy*, 19(2):111–118, May 2003. ISSN 02659646. doi: 10.1016/S0265-9646(03)00016-X. URL <http://linkinghub.elsevier.com/retrieve/pii/S026596460300016X>. (Not cited.)
- [25] I. Crawford. The scientific case for human space exploration. *Space Policy*, 17(3):155–159, Aug. 2001. ISSN 02659646. doi: 10.1016/S0265-9646(01)00020-0. URL <http://linkinghub.elsevier.com/retrieve/pii/S0265964601000200>. (Not cited.)
- [26] F. A. Cucinotta. Space radiation cancer risk projections for exploration missions: uncertainty reduction and mitigation, 2001. URL <http://spaceflight.nasa.gov/shuttle/support/researching/radiation/marsrisk.pdf>. (Not cited.)
- [27] J. Curtis, L. Harra, J. Zarnecki, and M. Grady. Reviewing UK space exploration. *Space Policy*, 26(2):113–116, May 2010. ISSN 02659646. doi: 10.1016/j.spacepol.2010.03.007. URL <http://linkinghub.elsevier.com/retrieve/pii/S0265964610000366>. (Not cited.)
- [28] R. C. DeCharms. Applications of real-time fMRI . *Nature Reviews Neuroscience*, 9:720–729, 2008. (Cited on page 21.)
- [29] S. J. Dick and R. D. Launius, editors. *Societal Impact of Spaceflight*. NASA, Washington, D.C., 2007. (Not cited.)
- [30] a. Dupas and J. Logsdon. Creating a productive international partnership in the Vision for Space Exploration. *Space Policy*, 23(1):24–28, Feb. 2007. ISSN 02659646. doi: 10.1016/j.spacepol.2006.11.003. URL <http://linkinghub.elsevier.com/retrieve/pii/S0265964606001056>. (Not cited.)
- [31] P. Ehrenfreund, N. Peter, and L. Billings. Building long-term constituencies for space exploration: The challenge of raising public awareness and engagement in the United States and in Europe. *Acta Astronautica*, 67(3-4):502–512, Aug. 2010. ISSN 00945765. doi: 10.1016/j.actaastro.2010.03.002. URL <http://linkinghub.elsevier.com/retrieve/pii/S0094576510000822>. (Not cited.)
- [32] a. Ellery. Humans versus robots for space exploration and development. *Space Policy*, 19(2):87–91, May 2003. ISSN 02659646. doi: 10.1016/S0265-9646(03)00014-6. URL <http://linkinghub.elsevier.com/retrieve/pii/S0265964603000146>. (Not cited.)

- [33] P. Ferguson and J. P. How. Formation Flying Experiments on the Orion-Emerald Mission. In *Proceedings of AIAA Space 2001 Conference*, 2001. (Not cited.)
- [34] P. Finarelli and I. Pryke. Implementing international co-operation in space exploration. *Space Policy*, 22(1):23–28, Feb. 2006. ISSN 02659646. doi: 10.1016/j.spacepol.2005.11.012. URL <http://linkinghub.elsevier.com/retrieve/pii/S0265964605001153>. (Not cited.)
- [35] P. Finarelli and I. Pryke. Building and maintaining the constituency for long-term space exploration. *Space Policy*, 23(1):13–19, Feb. 2007. ISSN 02659646. doi: 10.1016/j.spacepol.2006.11.001. URL <http://linkinghub.elsevier.com/retrieve/pii/S0265964606001111>. (Not cited.)
- [36] R. Fisackerly, C. Reimers, and a. Pradier. Exploration system technology aspects in the exploration programme of the European Space Agency. *Acta Astronautica*, 59(1-5):3–12, July 2006. ISSN 00945765. doi: 10.1016/j.actaastro.2006.02.017. URL <http://linkinghub.elsevier.com/retrieve/pii/S0094576506001196>. (Not cited.)
- [37] B. Foing and P. Ehrenfreund. Journey to the Moon: Recent results, science, future robotic and human exploration. *Advances in Space Research*, 42(2):235–237, July 2008. ISSN 02731177. doi: 10.1016/j.asr.2008.03.011. URL <http://linkinghub.elsevier.com/retrieve/pii/S0273117708001646>. (Not cited.)
- [38] A. Forrest, B. Laval, D. Lim, D. Williams, A. Trembanis, M. Marinova, R. Shepard, A. Brady, G. Slater, and M. Gernhardt. Performance evaluation of underwater platforms in the context of space exploration. *Planetary and Space Science*, 58(4):706–716, Mar. 2010. ISSN 00320633. doi: 10.1016/j.pss.2009.08.007. URL <http://linkinghub.elsevier.com/retrieve/pii/S0032063309002475>. (Not cited.)
- [39] G. E. Gauger^b, C. A. Tobias^b, T. Yang^b, and M. Whitney^b. The effect of space radiation on the nervous system. *Advances in Space Research*, 6(11):243–249, 1986. URL http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V3S-472BJ54-3F&_user=141903&_coverDate=12/31/1986&_rdoc=1&_fmt=high&_orig=search&_sort=d&_docanchor=&view=c&_searchStrId=1410022796&_rerunOrigin=google&_acct=C000011778&_version=1&_urlVersion=0&_userid=141903&md5=5829460965049b158942dad85c3382d. (Not cited.)
- [40] R. B. Gordon, M. Bertram, and T. E. Graedel. Metal stocks and sustainability. *Proceedings of the National Academy of Sciences of the United States of America*, 103(5):1209–1214, 2006. URL <http://www.ncbi.nlm.nih.gov/pubmed/16432205>. (Cited on page 15.)
- [41] M. Gruntman. Instrumentation for interstellar exploration. *Advances in Space Research*, 34(1):204–212, 2004. ISSN 02731177. doi: 10.1016/j.asr.2003.04.064. URL <http://linkinghub.elsevier.com/retrieve/pii/S0273117704002716>. (Not cited.)
- [42] T. Hammond, F. Lewis, T. Goodwin, R. Linnehan, D. Wolf, K. Hire, W. Campbell, E. Benes, K. O’Reilly, R. Globus, and J. Kaysen. Gene expression in space. *Nature*, 5(359), 1999. (Not cited.)
- [43] G. Horneck, A. Coradini, G. Haerendel, M.-B. Kallenrode, P. Kamoun, J. P. Swings, A. Tobias, and J.-J. Tortora. Towards a European vision for space exploration: Recommendations of the Space Advisory Group of the European Commission. *Space Policy*, 26(2):109–112, May 2010. ISSN 02659646. doi: 10.1016/j.spacepol.2010.02.007. URL <http://linkinghub.elsevier.com/retrieve/pii/S0265964610000238>. (Not cited.)
- [44] J. How. Orion Flight Model Hardware, 2010. URL <http://www.mit.edu/people/jhow/orion/>. (Not cited.)
- [45] J. P. How. GPS Sensing for Formation Flying, 2010. URL http://www.mit.edu/people/jhow/ff_leo.html. (Not cited.)
- [46] J. P. How. Relative Navigation for Formation Flying Spacecraft Using Carrier-Phase Differential GPS, 2010. URL <http://www.mit.edu/people/jhow/gps1.htm>. (Not cited.)
- [47] J. Huntington. Improving Satellite Protection with Nanotechnology, 2007. URL <http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA474825&Location=U2&doc=GetTRDoc.pdf>. (Not cited.)

- [48] S. Jähnichen, K. Brieß, and R. Burmeister. Flying Sensors & Swarms in Space. In B. Mahr and H. Sheng, editors, *Autonomous Systems & Self-Organization, Management, and Control*, pages 71–77, Shanghai, 2008. Springer. (Not cited.)
- [49] H. Jones, K. Yeoman, and C. Cockell. A pilot survey of attitudes to space sciences and exploration among British school children. *Space Policy*, 23(1):20–23, Feb. 2007. ISSN 02659646. doi: 10.1016/j.spacepol.2006.11.013. URL <http://linkinghub.elsevier.com/retrieve/pii/S0265964606001093>. (Not cited.)
- [50] A. Y. Kalery, I. V. Sorokin, and M. V. Tyurin. Human space exploration beyond the international space station: Role of relations of human, machine and the &IJEarth&IYF. *Acta Astronautica*, June 2010. ISSN 00945765. doi: 10.1016/j.actaastro.2010.06.009. URL <http://linkinghub.elsevier.com/retrieve/pii/S0094576510002006>. (Not cited.)
- [51] R. Kapfer, M. Krumme, and M. Davis. SBR sparse array performance with subarray orientation and timing errors. In *Proceedings of IEEE Radar Conference*, page 8 pp. IEEE Press, 2006. URL <http://dx.doi.org/10.1109/RADAR.2006.1631838>. (Not cited.)
- [52] J. T. Kare and K. L. G. Parkin. A Comparison of Laser and Microwave Approaches to CW Beamed Energy Launch. In *AIP Proceedings on the Fourth International Symposium on Beamed Energy Propulsion*, pages 388–399, 2006. (Not cited.)
- [53] L. B. King, G. G. Parker, S. Deshmukh, and J.-H. Chong. Spacecraft Formation-flying using Inter-vehicle Coulomb Forces, 2002. URL http://www.niac.usra.edu/files/studies/final_report/601King.pdf. (Not cited.)
- [54] J. M. Laffleur and J. H. Saleh. Survey of intra- and inter-mission flexibility in space exploration systems. *Acta Astronautica*, 67(1-2):97–107, July 2010. ISSN 00945765. doi: 10.1016/j.actaastro.2009.12.004. URL <http://linkinghub.elsevier.com/retrieve/pii/S0094576509005761>. (Not cited.)
- [55] R. D. Launius. The historical dimension of space exploration: reflections and possibilities. *Space Policy*, 16(1): 23–38, Feb. 2000. ISSN 02659646. doi: 10.1016/S0265-9646(99)00055-7. URL <http://linkinghub.elsevier.com/retrieve/pii/S0265964699000557>. (Not cited.)
- [56] D. F. Lester and M. Robinson. Visions of exploration. *Space Policy*, 25(4):236–243, Nov. 2009. ISSN 02659646. doi: 10.1016/j.spacepol.2009.07.001. URL <http://linkinghub.elsevier.com/retrieve/pii/S0265964609000691>. (Not cited.)
- [57] G. Lockwood and F. Foster. Design of sparse array imaging systems. In *Proceedings on IEEE Ultrasound Symposium*, pages 1237–1243, 1995. (Not cited.)
- [58] J. Logsdon. Why space exploration should be a global project. *Space Policy*, 24(1):3–5, Feb. 2008. ISSN 02659646. doi: 10.1016/j.spacepol.2007.11.007. URL <http://linkinghub.elsevier.com/retrieve/pii/S0265964607001178>. (Not cited.)
- [59] M. Y. MacLeish and W. A. Thomson. Global visions for space exploration education. *Acta Astronautica*, 66 (7-8):1285–1290, Apr. 2010. ISSN 00945765. doi: 10.1016/j.actaastro.2009.09.030. URL <http://linkinghub.elsevier.com/retrieve/pii/S0094576509004822>. (Not cited.)
- [60] Marco R, González-Jurado J, Calleja M, Garesse R, Maroto M, Ramírez E, Holgado MC, de Juan E, and Miquel J. Microgravity effects on *Drosophila melanogaster* development and aging: Comparative analysis of the results of the fly experiment in the Biokosmos 9 biosatellite flight. *Advances in Space Research*, 12(1):157–166, 1992. URL <http://www.ncbi.nlm.nih.gov/pubmed/11536953>. (Not cited.)
- [61] P. Messina and D. Vennemann. The European space exploration programme: Current status of ESA’s plans for Moon and Mars exploration. *Acta Astronautica*, 57(2-8):156–160, July 2005. ISSN 00945765. doi: 10.1016/j.

- actaastro.2005.03.020. URL <http://linkinghub.elsevier.com/retrieve/pii/S0094576505001116>. (Not cited.)
- [62] M. S. Miller and T. S. Keller. *Drosophila melanogaster* (fruit fly) locomotion during a sounding rocket flight. *Acta Astronautica*, 62(10-11):605–616, 2008. (Not cited.)
- [63] J. L. Mohammed. Mission Planning for a Formation-Flying Satellite Cluster. In I. Russell and J. F. Kolen, editors, *Proceedings of the Fourteenth International Florida Artificial Intelligence Research Society Conference*, pages 58–62. AAAI Press, 2001. URL <http://portal.acm.org/citation.cfm?id=646814.708008>. (Not cited.)
- [64] C. Oliver. The virtual space exploration education portal. *Acta Astronautica*, 61(1-6):548–552, June 2007. ISSN 00945765. doi: 10.1016/j.actaastro.2007.01.062. URL <http://linkinghub.elsevier.com/retrieve/pii/S0094576507000768>. (Not cited.)
- [65] N. Peter and K. Stoffl. Global space exploration 2025: Europe’s perspectives for partnerships. *Space Policy*, 25(1): 29–36, Feb. 2009. ISSN 02659646. doi: 10.1016/j.spacepol.2008.12.009. URL <http://linkinghub.elsevier.com/retrieve/pii/S0265964608001033>. (Not cited.)
- [66] S. Pyne. The extraterrestrial Earth: Antarctica as analogue for space exploration. *Space Policy*, 23(3):147–149, Aug. 2007. ISSN 02659646. doi: 10.1016/j.spacepol.2007.06.006. URL <http://linkinghub.elsevier.com/retrieve/pii/S0265964607000550>. (Not cited.)
- [67] M. C. Ridding and J. C. Rothwell. Is there a future for therapeutic use of transcranial magnetic stimulation? . *Nature Reviews Neuroscience*, 8:559–567, 2007. (Cited on page 22.)
- [68] M. Ries-Kautt. Crystallogenes studies in microgravity with the Advanced Protein Crystallization Facility on SpaceHab-01. *Journal of Crystal Growth*, 181(1):22, 1997. (Not cited.)
- [69] L. Salerno. Cryogenics and the human exploration of Mars. *Cryogenics*, 39(4):381–388, Apr. 1999. ISSN 00112275. doi: 10.1016/S0011-2275(99)00043-0. URL <http://linkinghub.elsevier.com/retrieve/pii/S0011227599000430>. (Not cited.)
- [70] I. S. U. Ssp. MiNI : From Tiny to Infinity. 2006. (Not cited.)
- [71] C. Stadd and J. Bingham. The US civil space sector: alternate futures. *Space Policy*, 20(4):241–252, Nov. 2004. ISSN 02659646. doi: 10.1016/j.spacepol.2004.08.001. URL <http://linkinghub.elsevier.com/retrieve/pii/S0265964604000542>. (Not cited.)
- [72] P. Suppes, Z.-L. Lu, and B. Han. Brain wave recognition of words. *Proceedings of the National Academy of Sciences of the United States of America*, 94(26):14965–14969, 1997. (Cited on page 21.)
- [73] M. A. Tamamoto. Active Antennas and UHF Antennas for Cubesat applications. (Not cited.)
- [74] K. M. Taming and R. A. Hafley. Electron Beam Freeform Fabrication for Cost Effective Near-Net Shape Manufacturing, 2006. URL <http://ntrs.nasa.gov/search.jsp?R=540654&id=4&as=false&or=false&q=Ns%3DHarvestDate%257c1%26N%3D4294697965>. (Cited on page 14.)
- [75] D. Tralli, R. Blom, V. Zlotnicki, A. Donnellan, and D. Evans. Satellite remote sensing of earthquake, volcano, flood, landslide and coastal inundation hazards. *ISPRS Journal of Photogrammetry and Remote Sensing*, 59(4):185–198, June 2005. ISSN 09242716. doi: 10.1016/j.isprsjprs.2005.02.002. URL <http://linkinghub.elsevier.com/retrieve/pii/S0924271605000043>. (Not cited.)
- [76] A. Vergara, B. Lorber, C. Sauter, R. Giegé, and A. Zagari. Lessons from crystals grown in the Advanced Protein Crystallisation Facility for conventional crystallisation applied to structural biology. *Biophysical Chemistry*, 118 (2-3):1590–1595, 2005. (Not cited.)

- [77] M. C. Vigan, G. Toso, P. Angeletti, I. E. Lager, A. Yarovoy, and D. Caratelli. Sparse Antenna Array for Earth-coverage Satellite Applications. In *4th European Conference on Antennas and Propagation (EuCAP 2010)*, Barcelona, 2010. (Not cited.)
- [78] A. M. Womack, B. J. M. Bohannon, and J. L. Green. Biogeography of the air. Presented by Green at the British Academy in July 2010. (Cited on page 17.)
- [79] M. Woodell. Power from space: the policy challenge. *Space Policy*, 16(2):93–97, May 2000. ISSN 02659646. doi: 10.1016/S0265-9646(00)00009-6. URL <http://linkinghub.elsevier.com/retrieve/pii/S0265964600000096>. (Not cited.)
- [80] D. Yang, Y. Zhou, and Y. Wang. Remote Sensing with Reflected Signals: GNSS-R Data Processing Software and Test Analysis, 2009. URL <http://www.insidegnss.com/auto/sepoct09-Yang.pdf>. (Not cited.)
- [81] S. Yatabe and A. Fabbri. The application of remote sensing to canadian petroleum exploration: promising and yet unexploited. *Computers & Geosciences*, 12(4):597–609, 1986. ISSN 00983004. doi: 10.1016/0098-3004(86)90070-1. URL <http://linkinghub.elsevier.com/retrieve/pii/0098300486900701>. (Not cited.)
- [82] Y. Zhou. Perspectives on Sino-US cooperation in civil space programs. *Space Policy*, 24(3):132–139, Aug. 2008. ISSN 02659646. doi: 10.1016/j.spacepol.2008.06.002. URL <http://linkinghub.elsevier.com/retrieve/pii/S0265964608000404>. (Not cited.)

Glossary

gyrotron a type of high-powered microwave transmitter. [16](#)

specific impulse (I_{sp}) is a metric of rocket (or jet) efficiency; the change in momentum per unit amount of propellant used. (This works out to an SI unit of seconds.) The higher the specific impulse, the less propellant is needed to gain a given amount of momentum. For example, the Space Shuttle Main Engine has an I_{sp} of 453s. [7](#)

Acronyms

CLSS Closed-Loop Life Support Systems: are life support systems which reuse 100% of their waste resources, with the exception of waste energy. [8](#)

COSPAR Committee on Space Research: COSPAR promotes international scientific research in space, and provides an open forum for the discussion of problems related to space science (for instance, organizing conferences on planetary protection policy).. [9](#)

EBFF Electron Beam Freeform Fabrication. [14](#)

ISRU In-Situ Resource Utilization: refers to the usage of local resources, especially the local usage of resources found in space, as opposed to the transport of Earth resources into space or vice versa. [7](#)

ITAR International Traffic in Arms Regulations: a set of United States federal regulations that restrict the international trade of items and information which is considered by the federal government to be “munitions,” including encryption technology and space technology. [9](#)

LEO Low Earth Orbit. [7](#)

SLS Selective Laser Sintering. [14](#)

SSTO Single Stage to Orbit: refers to a vehicle which reaches orbit without jettisoning hardware, expending only fluids. The term usually, but not exclusively, refers to reusable vehicles. [7](#)

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