EXPONENTIAL TECHNOLOGY IMPACT REPORT

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SPACE

Contents

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, 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

This report presents a number of ways to view the future of space exploration technology. From an outline of the problem space—derived from the level-1 categories of Getting There, Staying There, Human Exploration, Robotic Exploration, Using Space Resources, and Education—to detailed scenarios basic on specific technical solutions, we aim to cover the impact of all exponential technologies on space exploration.

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 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 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 specific impulse 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 coloines**
    * In Low Earth Orbit: 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 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$\longleftrightarrow$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**
    * ITAR restrictions: Need a framework for international cooperation in the private sector
    * Space treaties: Need 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.

2.3 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 seven different domains will play in the solution to these problems.

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:

Heatmap Scale					
HIGHEST IMPACT	HIGH IMPACT	IMPACT	LOW IMPACT	LOWEST IMPACT	NO IMPACT

	AI / Robotics	Biotech	Nanotech	Info / Networks	Neuro / Med	Policy / Law / Ethics	Entrepreneurship
Getting there							
Transportation							
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							
Terraforming							
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							
Bio-Regenerative Closed loop life support systems							
Food							
Water							
Waste							
Air							
Human Health							
Radiation Shielding							
Extreme habitat design							
Psycological well being							
Pharmacological support							
Political and Cultural Challenges							
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

Contents of this Section

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 [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 prohibitavely 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 gyroton (high-power microwave transmitter) increases over time, and the cost of each gyrotron decreases over time. The maximum power output of each individual gyroton 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. Gyrotons will get cheaper as the 3D printing of materials gets cheaper over time and 3D printing technology increases in capability. Also, the gyroton 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 beome 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 resiliance 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 solicitated 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 electrial 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 cleaniness 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 prioriy

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 instace 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»

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Glossary

LEO Low Earth Orbit. 4

SSTO Single Stage to Orbit: a vehicle which reaches orbit without jettisoning hardware, expending only fluids. The term usually, but not exclusively, refers to reusable vehicles. 4

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