EXPONENTIAL TECHNOLOGY IMPACT REPORT

DRAFT

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Singularity University

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.

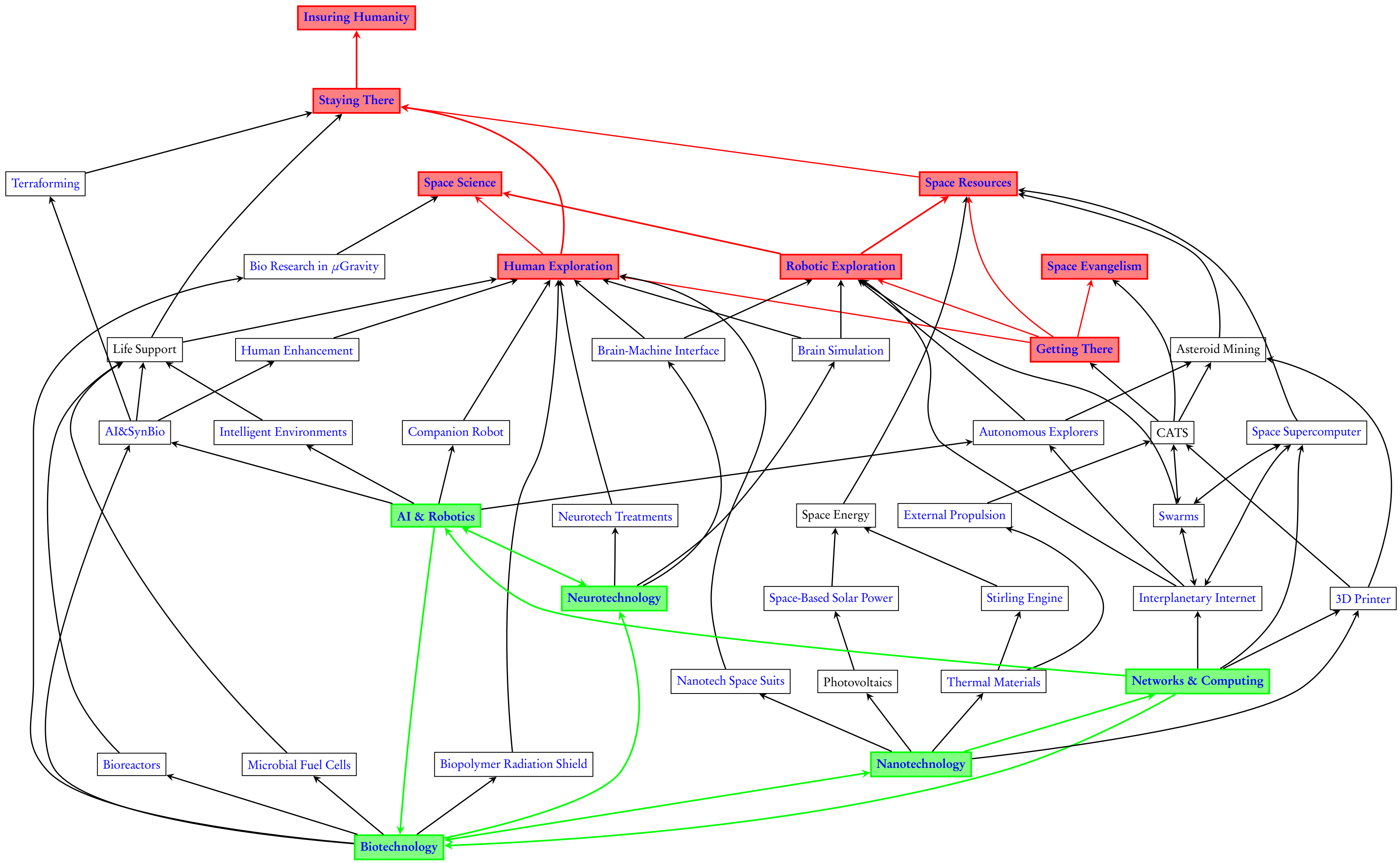
This report focuses on applications of exponential technologies that may facilitate the eventual establishment of a permanent human presence in space. These steps include the development of technologies to reduce the barriers to entry into space, technologies that may be needed to remain in space indefinitely (while also being useful on Earth), practical strategies to use resources which are off Earth, 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

This report is organized in three major sections - first, the aspects of the problem space are laid out, then the exponential technologies we are considering are described, and finally, we identify a number of opportunities where these converge.

1.1.1 Digraph

This diagram is an attempt to capture as much of the scope of this report as possible in a single-page graphic. Omission from this graphic is not intended as significant information; space and time were merely limited. The red boxes represent aspects of the problem space (subsections of section 2), the green boxes represent exponential technologies (subsections of section 3), and the white boxes represent themes in our exponential technology opportunities (described in section 4). The graph is organized top-down, so to tell a story, one should follow the arrows from the bottom up—from the basic enabling technologies through to the grand challenges.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2 Aspects of the Problem Space

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.

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

2.1 Insuring Humanity

"I don't think the human race will survive the next thousand years, unless we spread into space. There are too many accidents that can befall life on a single planet. But I'm an optimist. We will reach out to the stars."

– **Stephen Hawking**, interview with Daily Telegraph, 2001

The human race is young and susceptible to damage and destruction, both from events outside our control such as asteroid impact, but also increasingly from dangers stemming from human-created technologies such as biological warfare. As Carl Sagan put it, "in the long run, every planetary civilization… is obliged to become spacefaring… for the most practical reason imaginable: staying alive... If our long-term survival is at stake, we have a basic responsibility to our species to venture to other worlds." In this light, the benefits of traveling to space outweigh the risks, even when reasons of scientific discovery and the possibility of commercial profit are removed from the equation. We must lift our eyes and extend humanity's reach beyond our little drop of water and earth, and into the vast oceans and lands that await.

2.2 Getting There

The key problem driving the cost of space access today is fundamental inefficiency of chemical rockets. In the year 2010 payloads are delivered into orbit the same way they were launched in 1960s: by exploding large amounts of chemicals in a semi-controlled way. Conventional multistage rockets are limited to payload fractions of less than 4%. Using the ideal rocket equation, it is easy to see that this inefficiency is caused partly by the structural limits of existing materials, and partly by the limited specific impulse (I_{sp}) of chemical propellants, which have reached a practical limit of 453 seconds.

Inefficiency of chemical propulsion results in unreasonable complexity of present day launch vehicles, which operate on the very limits of structural margins. This requires a large number of people to work on the maintenance, operation and pre-flight checks. It also prevents reusability of rockets, leading to unacceptably high risks associated with launch and extremely high costs of payload insurance. Launch of a chemical rocket is a violent process and a structure operating near its design tolerance is more susceptible to fatigue and failure. The Space Shuttle, as a reusable vehicle, requires extensive refurbishment and safety checks between launches, to the extent that the launcher is disassembled, inspected, refurbished and rebuilt before every launch. For example, a hydrogen tank used for the on-board fuel cell is manufactured to burst at 1.5 times its usual operating pressure in order to save mass, but this safety factor of 1.5 means the tank may last only 100 cycles. Such a failure-prone component must have a more regular inspection regime, so operational costs go up. In contrast, the fuselage of a pressurized civil aircraft has a safety factor of two, and for that relatively little extra mass will last tens of thousands of pressurization cycles.

The high cost of space launch arises not only from technical challenges but also from the absence of economic incentives and the lack of a well defined market. Although, we would argue, those economical challenges will be eliminated as soon as the technical challenges of building cheap and reliable launch vehicles are resolved. On the economic side, various market models predict an essentially flat elasticity of demand for space access until the cost of launch is reduced below $1000 per kilogram[59]. (See Figure 1.) This implies that the primary economic benefits of space cannot be

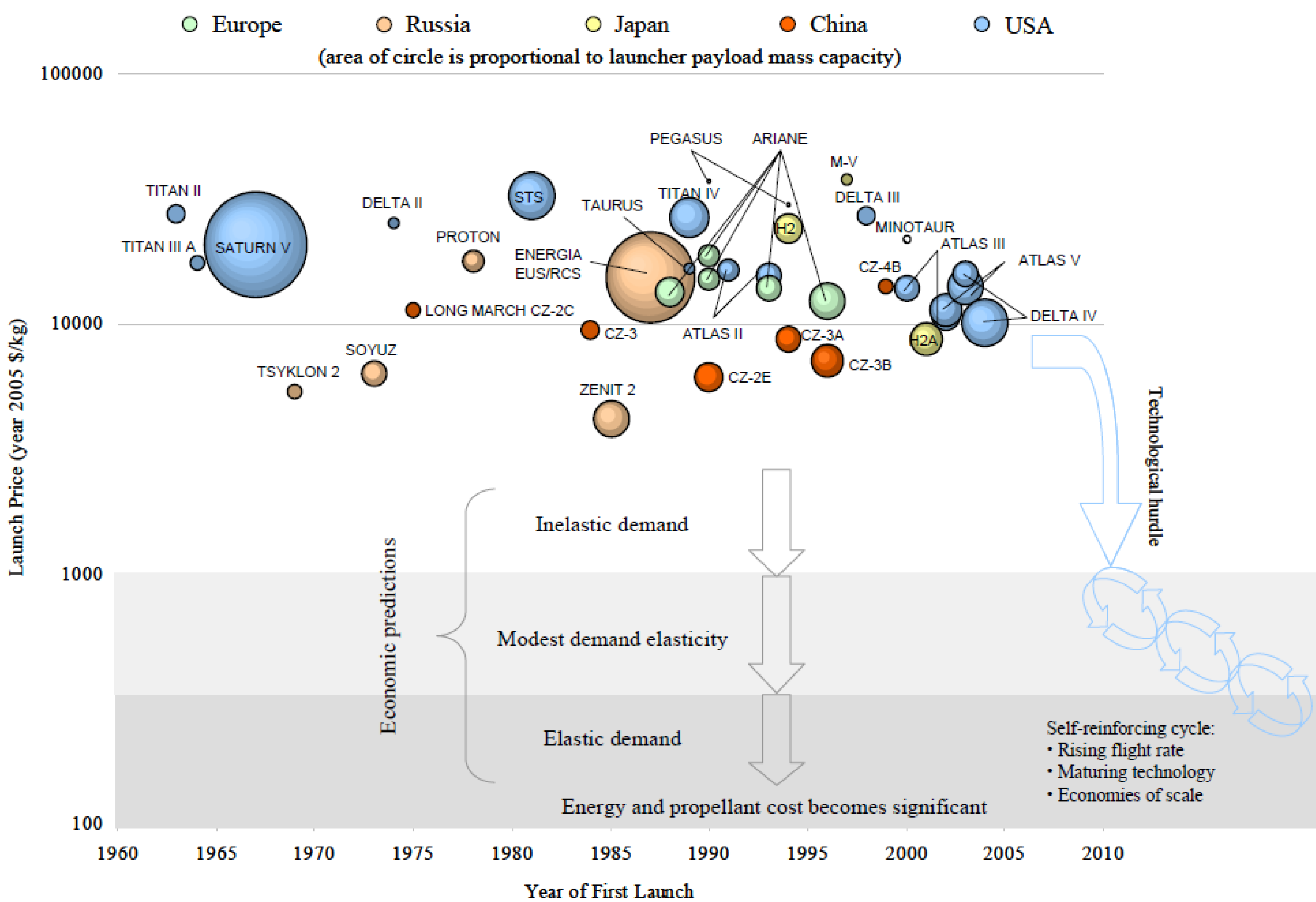

Figure 1. Cost of space access over the last 5 decades

realized without an order of magnitude reduction in launch costs and hence, without a paradigm shift in the means of space launch systems.

An additional problem that is deeply rooted in the inefficiency of chemical rockets and the absence of mature space exploration market is lack of mass produced cheap components for space launch systems. All critical components are custom produced and tested by large teams over long periods of time. This leads into yet another problem: the time lags between the payload production and launch are unacceptably long and can hardly fit into business models of small- and medium-sized businesses which demand expediency as they are driven by the demand of rapid growth. Moreover, the current way of space transportation often requires high level of integration between the launch vehicle and the payload, which means that the customer is forced to choose the supplier long in advance and coordinate the development of payload with the launch provider.

In summary, launch is currently almost prohibitively expensive, infrequent, and inconvenient. Any transformative change in the landscape of space activity will require more effective launch systems.

2.3 Staying There

The conditions we have to create in space for human life to thrive are to some extent the same humans need to create in order to stay on Earth. As we need to create conditions on Earth which are conducive to life, so have we in space.

However, between the two environments there are some fundamental differences. In space the key challenges derive from: lack of breathable air/atmosphere; lack of all other life support systems, services, and goods/materials provided on Earth by Nature, as well as extreme temperatures; radiation; absence of or reduced gravity; different light-dark patterns; reduced number of people, at least in the early stages of space colonization, isolation, and reduced availability of physical space.

A space system inhabitable by humans, at least given present technologies, should be designed in order to become, at a certain point, closed for matter and open for energy. All the living parts and beings would be interconnected and interdependent, as well as diverse and symbiotic.

Staying in a space environment, either grounded or ungrounded, requires the respect of three fundamental principles:

1. People in the space environment should not be subject to increasing concentrations of substances produced by human activity, such as molecules or chemical substances which if not removed would accumulate in air, soil, water, or other materials (for example CO_2, CH_4, other chemical substances).

2. In a thriving space environment the fundamental life support systems should be recreated and operated in a reliable way, indefinitely in time. Through photosynthesis, or other processes achieving a similar result, the space life-support systems should be able to regenerate order and structure for human use, starting from higher levels of disorder, using external energy sources.

3. In space settlements people should not subject to conditions that systematically compromise their capacity to satisfy their fundamental human needs. Human needs can be classified in nine categories, in four domains—Being (qualities), Having (things), Doing (actions), Interacting (settings)—and all should be satisfied for a healthy and thriving life:

Fundamental Human Needs	Being	Having	Doing	Interacting
subsistence	physical and mental health	food, shelter, work	feed, clothe, rest, work	living environment, social setting
protection	care, adaptability, autonomy	social security, health systems, work	co-operate, plan, take care of, help	social environment, dwelling
affection	respect, sense of humour, generosity, sensuality	friendships, family, relationships with nature	share, take care of, make love, express emotions	privacy, intimate spaces of togetherness
understanding	critical capacity, curiosity, intuition	literature, teachers, policies, educational	analyse, study, meditate, investigate	schools, families, universities, communities
participation	receptiveness, dedication, sense of humour	responsibilities, duties, work, rights	cooperate, dissent, express opinions	associations, parties, churches, neighborhoods
leisure	imagination, tranquillity, spontaneity	games, parties, peace of mind	day-dream, remember, relax, have fun	landscapes, intimate spaces, places to be alone
creation	imagination, boldness, inventiveness, curiosity	abilities, skills, work, techniques	invent, build, design, work, compose, interpret	spaces for expression, workshops, audiences
identity	sense of belonging, self-esteem, consistency	language, religions, work, customs, values, norms	get to know oneself, grow, commit oneself	places one belongs to, everyday settings
freedom	autonomy, passion, self-esteem, open-mindedness	equal rights	dissent, choose, run risks, develop awareness	anywhere

If humans in space should be deprived of the capacity to satisfy any of the needs above, in a sufficiently abrupt manner or for a sufficiently long time duration, they would face a mental and/or physical poverty at first, and eventually, if the deprivation persists, they could be led to death. Any relational or governance system established in a space environment, especially with the goal of "staying there," should consider all the fundamental human needs above. It should be noticed that while the satisfiers of the needs change across cultures, or time, the needs themselves remain constant. For this reason, a space environment and space activities should be designed to maximize the satisfaction of the human needs without violating the previous principles. This result can often be conveniently achieved through dematerialization, which becomes more and more effective with the advancement of exponential technologies such as augmented virtual reality. The fundamental design principles for human interaction in space could be the "Golden Rule": "Would I like to be subject to such conditions I am creating?"

Once the design principles above have been considered, the challenge remains how to implement them in the extreme space environment.

2.4 Human Exploration

Human exploration beyond Earth's atmosphere presents many threats and promises to meeting basic human needs: The conditions are inhospitable to human life. There is no known air source. The temperatures are extreme. Radiation is intense. Meteor showers, solar flares, debris and dust are ever-present threats. Human–rated infrastructures and outposts do not exist. Other forms of life have yet to be found. The challenges associated with understanding and preparing for optimum general human wellbeing in space is multitudinous. The recommendation, risk assessment and mitigation (be it technology, countermeasure development or advanced life supports and protocols) for the enhanced well being, performance, operation and happiness of the crews is imperative.

Closed Loop Life Support Systems (CLLSS)

The CLLSS components, resources and technologies needed to provide a basic foundation for a live-able, controllable and recoverable environment for human space flight and habitability must include the following space-rated systems:

- Atmospheric Revitalization
- Water Recovery
- Waste Management
- Habitation System
- Environmental Monitoring
- Pressure Control
- Fire Protection
- Thermal Control

NASA's ECLASS can only achieve a 65% closed loop effectiveness with current systems technology (Figure 2). This is acceptable for short duration human space flight and life onboard the International Space Station (ISS), but it does not suffice for further human exploration.

Food: Need for a way to generate a complete, well rounded diet with minimal input and output, 100% closed loop if possible. Bonus: enjoyable to eat.

Water: Need: Sophisticated waste and grey water systems to allow for closed loop water systems.

Waste: Design waste out of the system. Design and engineer systems able to operate completely in loops closed for matter and open for energy.

Air: Assure fully recyclable air systems able to work indefinitely at 100% reliability.

Reliable fully closed loop life support systems for humans (Figure 3) need to be demonstrated in ground test facilities and in space with increased performance efficiencies such that little-to-no-maintenance, re-supply and the capacity for bio-regeneration is incorporated into the design metrics towards future autonomous space system adaptation and in situ resource utilization. We must advance, demonstrate, and integrate current space rated hardware with new technologies and strategies to also reduce the mass, power and re-supply requirements when measured against the current state of the art space flight qualified hardware and work towards both the issues of human survivability and longevity whilst in space.

Human Factors

Extreme environment architectures and habitat design greatly impact human performance, behaviors and limits in everyday life as equally as instances of great stress. As we know it, life in the space environment presents many challenging factors for the crew including: conditions of prolonged confinement, isolation, information saturation, performance pressure, constant monitoring, time delays, unnatural lighting, limited color palette and seasonal change, limited personal space, restricted access, thermal difference, the reliance on reconstituted air, water, tactile starvation and increasing physical acclimation as a result of radiation and microgravity. Reliability and diversity are equal yet opposite needs for optimum human habitat design in extreme environments.

Extreme Design

Human-rated structures and habitable architectures for use in extreme environments such as space must satisfy very unique requirements. Temperature extremes, gravity, shielding from solar and cosmic radiation and micro-meteoroid impacts, vacuum / internal pressurization, abrasive and toxic materials such as planetary dust must be factored into

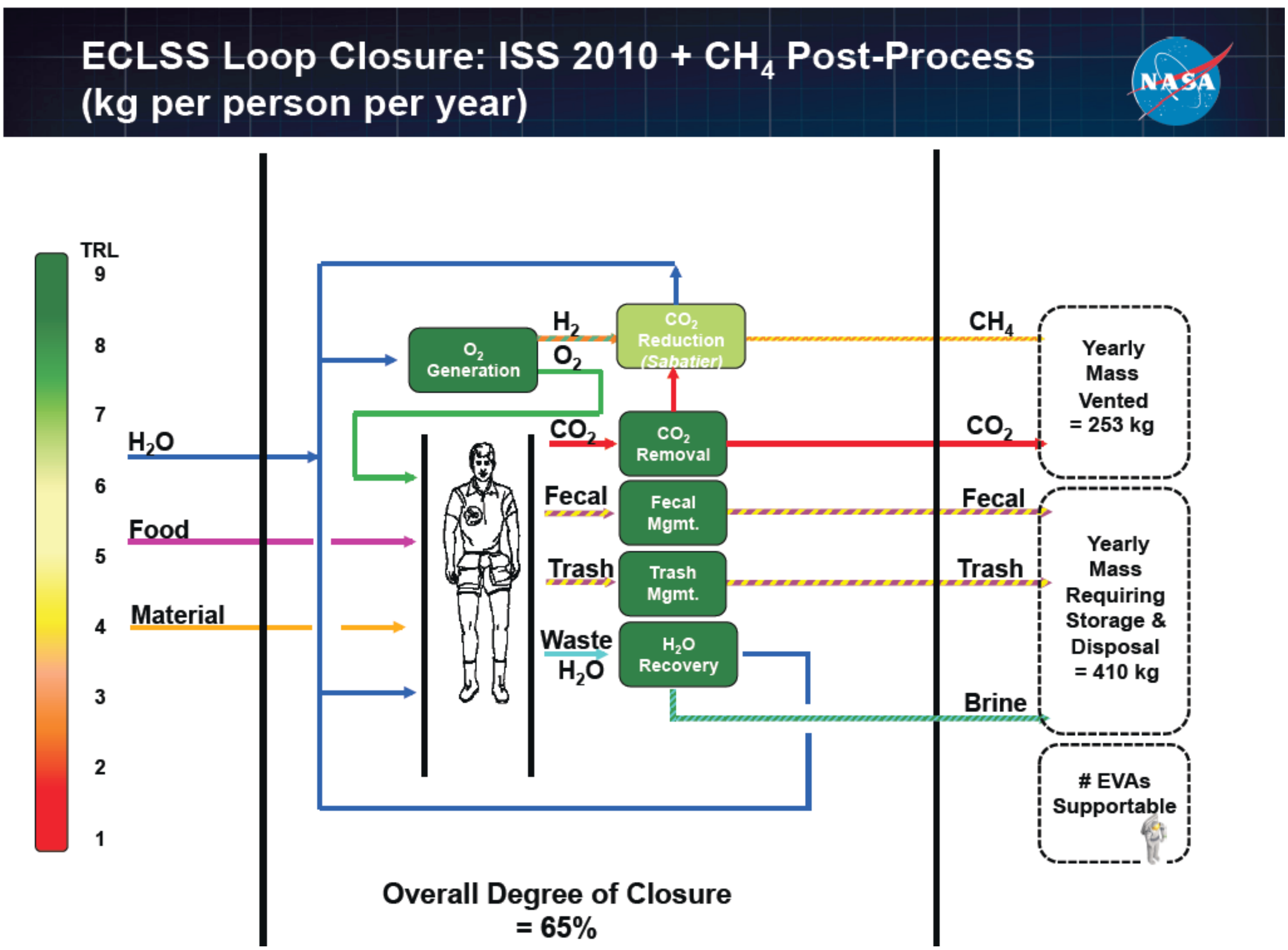

Figure 2. ECLSS Loop Closure: ISS 2010 + CH_4 Post-Process (kg pp/py) = 65% effectiveness [113]

design requirements. These issues pose great challenges to the structural adequacy, materials science and maintenance, compatibility, functionality, access and cost of suitable architectures and structures.

Physiological Health

Physiological acclimation in space flight is complex and diverse involving multiple systems (Figure 4). Past, present and future countermeasures in space flight require ongoing and additional review. Evidence of μgravity-induced physiological acclimation is known. Evaluations on crews in space analogue environments, space flight and ISS flights are ongoing yet the long term effects yet to be fully known and mitigated. Medical risks variable and the delivery of medical interventions, preventions and care needs to be refined. The effects of microgravity and radiation are the most problematic to human exploration in space. For instance, reliable and suitable materials technology, design and mitigation for radiation are needed. Acceptable radiation exposure limits need to be established. Alert/warning and communications infrastructure from pre-screening, to initial construction through to settlement phases need to be formalized to analyze the long-term health risks. Microgravity (from muscle atrophy, vestibular and ocular disturbance, venous pooling to sleep disturbance and sanitation issues) have been evidenced and greatly impact crew performance, health and well being, thus impacting on the entire mission.

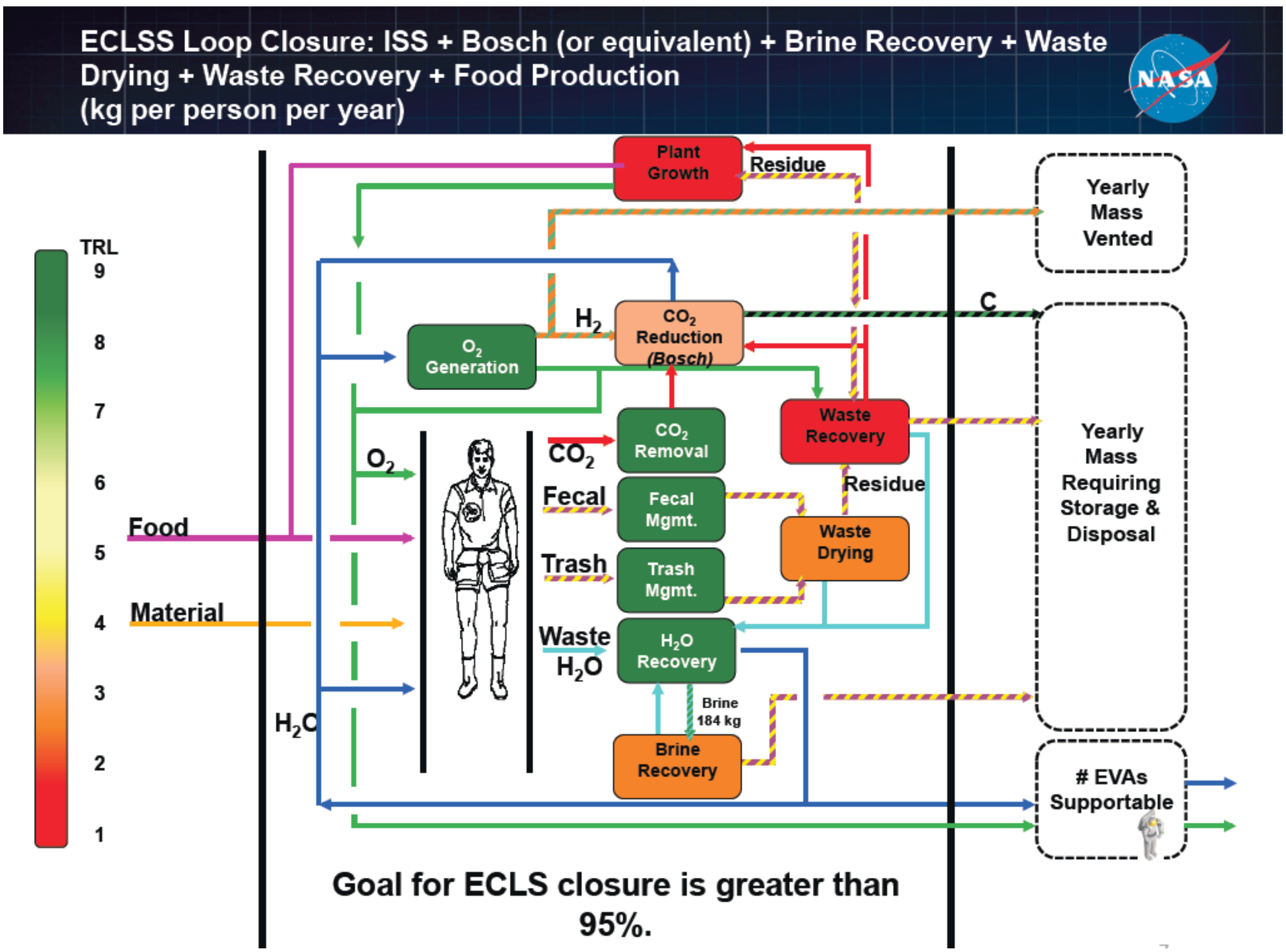

Figure 3. ECLSS Loop Closure: ISS + Bosch (or equivalent) + Brine Recovery + Waste Drying + Waste Recovery + Food Production (kg pp/yr) = 95% effectiveness [113]

Physiologic effects	Launch	Duration of flight			Landing	Postflight period		
		24 h	48 h 2 wk	> 1 mo		24–48 h	1–2 mo	> 1 yr
Fluid redistribution	• Redistribution of fluid to the torso and head • 10% decreased fluid volume in the legs	• 17% reduction in plasma volume	• Gradual decrease in erythropoietin secretion, leading to a 10% decrease in total blood volume		• Orthostatic hypotension from pooling of fluids in the legs	• Return of normal fluid distribution		
Neurovestibular effects	• Space motion sickness				• Space motion sickness			
Muscle changes		• Gradual decrease in muscle mass by 20% • Gradual decrease in muscle strength (up to 50% loss observed)		• Gradual decrease in muscle mass by 30%	• Muscle soreness and tightness		• Full recovery of muscle mass and strength	
Bone demineralization		• 60%–70% increase in calcium loss (urinary, fecal). Reduced parathyroid hormone and vitamin D production. • Gradual loss of bone density (1%–2% per month)						• Complete or almost complete restoration of bone density
Psychosocial effects	• Fatigue, sleep debt, isolation, emotional effects, stress to the astronaut's family, multicultural crew environment							
Immune dysregulation		• Possible reactivation of latent herpes viruses and impairment of cell-mediated immunity			• Numerous cellular and other changes leading to impaired immunity		• Gradual improvement in immunity (days to weeks)	

Figure 4. Timeline of physiologic acclimation and acclimatization experienced by astronauts from launch to after return to earth[150]

Other problems include

1. Bone demineralization leading to space-related osteoporosis and vitamin loss
2. Temperature extremes
3. Circadian dysynchrony and sleep disturbance
4. High vacuum (decompression illness)
5. Space debris
6. Ionospheric plasma and
7. Acoustic noise

Countermeasure

One strategy for mitigating risks, stressors and ensuring supports for crews in space is through the development of countermeasures in addition to careful consideration of crew selection, appropriate training, extreme habitat design, human factors, social governance supports and societal infrastructures for long duration spaceflight. (See for instance Figure 5.) Future human exploration leading to "staying there" (subsection 2.3) will need to design protocols and policies for consent and justice for one-way missions and strategies for permanent colonisation with ethical micro and meso-social structures.

Physiologic effects; duration of flight	Before flight	During flight	After flight
Shift in body fluids (cardiovascular effects)			
Long and short duration	• None	• Exercise • Negative pressure suits for the lower body (to mechanically induce an earth-equivalent body fluid distribution while in space) • On re-entry: isotonic fluid taken orally,[2] use of a pressurized anti-gravity suit to minimize fluid pooling in the legs, use of a liquid cooling garment, recumbent position for astronauts on long-duration missions[3]	• The use of midodrine (to counter postflight orthostatic intolerance) is being considered
Space motion sickness (neurovestibular effects)			
Long and short duration	• Neurovestibular conditioning (virtual reality, parabolic or aerobatic flights) • Antinauseant medications	• Antinauseant medications[4] (promethazine, scopolamine[5]) often given with dextroamphetamine to counter sedation	• Intravenous antinauseant and fluid administration for severe postlanding syndrome
Muscle atrophy			
Long and short duration	• Resistance exercise program • Aerobic exercise program	• Exercise (aerobic and strength) monitored and modified by on-ground medical support team[6,7,8] • Others measures under consideration: electrical muscle stimulation, dietary supplementation with amino acids, artificial gravity (e.g., rotating spaceship)[6,7,8,9]	• Muscle conditioning and rehabilitation program, including a combination of adapted exercises, massages, icing and nonsteroidal anti-inflammatory agents
Bone demineralization			
Long and short duration	• 3 DXA scans per year		
Long duration	• 2 DXA scans within 6 months after flight	• Resistance exercises[10,11,12] • Diet supplemented with calcium and vitamins D and K[10,13] • Others measures under consideration: bisphosphonates; potassium citrate; parathyroid hormone; low magnitude, high frequency vibrations[10,11,14]	• 4 DXA scans over 3 years • Temporary restriction of some activities (e.g., flying high-performance jets)[14,15]
Psychosocial effects			
Long and short duration	• Specific criteria for recruitment[16,17] and specific behavioural competencies for assignment to missions • Didactic training, including teamwork in multicultural settings, and field-based training in leadership and followership skills	• Individualized work schedules monitored by ground support crew, with 8 hours rest per day • Short-acting hypnotics (to prevent sleep loss and cumulative sleep deficit) and modafanil (to enhance performance after periods of reduced sleep)	
Long duration			• Psychological debriefing sessions
Immune dysregulation			
Long and short duration	• Quarantine program • Restricted contact with general public for 1 week before flight	• Daily exposure to artificial gravity[18] and nutritional supplementation with nucleotides[19] are being considered	• Collection of biological samples to assess immune function

Note: DXA = dual energy x-ray absorptiometry.

Figure 5. Countermeasures to minimize risks to astronauts before, during and after spaceflight[150]

Today astronaut crews actively contribute and refine existing technologies and protocols to ensure best practices and environments for living and working based on their first-hand experience during space flight or mission; however the prevalent thought and practice today is essentially terrestrial. Countermeasures by their very nature, seek to provide supports consistent with the human need on Earth and thus have an inherent pedestrian and gravity-centric logic. Mitigating the optical disturbance of zero-gravity for instance by creating a false orientation with 'Up' signs and consistently angled writing provides crews with short-term adaptation solutions. The need for Lunar, Martian and general Astro-centric specific counter-measures and harness-measures will be required in the future if we are to ensure optimum performance and evolve as an adaptive and empowered space-faring and future space-dwelling species.

Psychological wellness

The psychological and related physical impacts of long duration space flight and extended human exploration into space on human performance, social interactions, group and community interactions, space-Earth relationships and crew-specific behaviours are critical to operations and overall mission success. Further research on the sources and impact of long duration space flight on crew health and incremental risk identification is needed in order to reclassify behavioural health risks and thus best-plan for eventual human colonisation of space. The need for autonomous medical care, self-care, remote care and communications strategies should be considered essential design requirements for Human Factors and Extreme Design architecture, Crew selection, pre-flight training, In-flight Procedure, and space-protocols.

2.5 Robotic Exploration

By default, much of space exploration today is highly dependent on robotic systems as well as on support by means of artificial intelligence. From the early days of space exploration on, humans sent robotic devices and satellites into space to sense, image and explore the space frontier. However, much of the robotic exploration systems provide only crude degrees of "intelligence." More often than not, systems in space lag 15 years or more behind technology available on earth, which is mostly due to safety requirements as well as extensive research and development cycles within the space industry.

Another phenomenon which goes along with this is a fundamental dispute over human vs. robotic space exploration of space. The underlying logic states that robots will facilitate the groundwork of exploration for humans to follow. At this stage, the human dream to explore and possibly colonize space is normally dominated by the premise to move our life support systems into space and onto other planets.

However, non-augmented human bodies need an earthlike environment almost to exact earth specifications. Earthlike atmospheres, which are changed by the very metabolism of the body being in it, water and hundreds of other needs from complex nutrients, molecules, to exercise, social and spatial requirements. Ironically, the body that gives us the primary medium for experiencing our surroundings is also the single largest barrier to traveling and experiencing space.

A long-term plan to visit space in human bodies is basically committing to the idea of bottling up earth and exploring space inside of an "earth-bottle," which entirely separates us from the extraordinary experiences the interplanetary universe offers us.

We argue that a new conceptual model to evolve space exploration should be based on the development of a new kind of humanoid robotics, super-human artificial intelligence as well as virtual representation of space exploration. In addition, the development of an inter/intrastellar smart network to connect all information-based agents, robots, vehicles, nodes and life-support systems is suggested to provide a collective intelligence approach within space.

Humanoid robots—robots with human-like bodies such as Asimo or Robonaut—will quickly increase in their sensory capacity, eventually exceeding perception capabilities of the human body. In limited ways we already see today how robots equipped with night vision capability, thermal imaging capability, radar, seismographs, EMI receivers, and so forth augment human sensing. However, we suggest that such humanoid robots are only the very beginning of this "body" evolution. As described later, exponential advances in neuroscience, nanotechnology and synthetic biology will allow for a super-human kind of robots, with many human-like characteristics. However, such robots can be augmented with sensing and actuation capabilities beyond human limitations and can be specifically customized for conditions in space. In addition, the development of a specific "super-human intelligence" for such robots provides significantly higher information processing, problem solving capabilities, as well as communication characteristics with other intelligences such as robots, networks, satellites and humans by means of a space-wide operating system (e.g. ETIR idea "Intelligent Space Operating System"). Human intellect can then be uploaded remotely, augmented by means of enhanced perception/sensing, and experienced individually as well as collectively. Super Human Intelligent robots for space exploration provide the benefit to be resistant to adverse conditions within space such as extreme temperatures, radiation and toxins. By default, they don't require oxygen, food, sleep, or sunlight and can be designed to be of higher emotional/psychological robustness compared to humans. Psychological, social and bodily characteristics can be dynamically shaped to be optimal for individual space missions and can be adapted over time. This new kind of robotic super-human space exploration is meant to open up channels of exploration and experience with a currently unimaginable level of perceptive richness and extended realism by means of augmented sensing. In addition, new kinds of virtual environments, brain-machine interfaces and multimodal feedback systems will allow us to navigate such experience at in virtual fashion at increasingly higher resolution and vividness. This can be shared by everyone on earth rather than by a few astronauts. We believe the future of mankind in space can, and will be more interesting, exciting, and inspiring than the current vision of exploration with a human earth-bound body – both can and should happen in a parallel initially. We believe we can explore the planets not just from the confines of a space suit or tin can on the surface, but from a spectrum of physical embodiments, beginning decades ago with space robots that sent back images for us to experience. We will then know exactly on earth what it feels like to stick a feet in the sand of Mars, to go for a space-walk, or to observe our planet as a swarm of satellites.

2.6 Space Resources

Human resource consumption increases as the population of the Earth increases and as each member of the population uses more resources, but the amount of resources available on the Earth remains fixed. Fortunately, we as a species are not limited to gathering these resources terrestrially. While we are facing a shortage of both raw materials[73] and energy[127] here on the planet, both of these resrouces are bountiful in our solar system and beyond.

This observation is by no means novel. Right now, though, at the dawn of this new decade, we find ourselves sitting on the brink of an inflection point with respect to the harvesting of space-based resources and bringing them back to Earth. For the first time, as a result of the convergence of several pivotal and game-changing exponentially accelerating technologies, it will not only be economically viable to supply and power Earth from space, it will be a necessity.

Terrestrial Shortage of Valuable Materials

There are currently not enough raw materials present on planet Earth for the world's current population to live with the quality of life of the modern developed world[73]. This shortage clearly poses a large problem for the sustained growth of humanity in the upcoming decades, for not only is it desirable for every human being to have access to the same level of technology as those living in the developed world, but those in the developed world strive to advance their technological. Among others, some of the most important of these scarce materials are platinum group metals[72].

As these scarce materials are mined and extracted from the Earth, they become more and more scarce, and as they become more scarce the cost of mining them and extracting them increases. Fortunately, virtually all of these terrestrially scarce materials are available in space and can be found in near-earth asteroids. In the past, the cost of mining these asteroids and returning their materials to the earth has been prohibitively expensive. However, in the upcoming five to twenty years, the convergence of a number of exponentially accelerating technologies will result in the cost of mining these asteroids decreasing exponentially. With the cost of mining these materials from the earth increasing with every passing year, and the cost of mining them from space decreasing every year, there will be a point in the near future where it is not only economically viable but economically imperative to mine asteroids and return their contents to Earth[72].

There are many advantages of mining near-earth objects for resources over obtaining the resources from Earth, even aside from terrestrial shortage. First of all, it is likely that a high percentage prospecting missions will successfuly find highly valuable asteroids, due to already well-established science for analyzing the composition of asteroidal bodies from Earth. The high-grade ore found in asteroids will make processing (extractive metallurgy) quite easy. No negotiations will be needed with existing landowners. Additionally, there are no environmental laws to be dealt with, and mining and waste disposal will not have any potentially destructive effecst on the terrestrial ecosystem. Asteroid mining systems will be highly scalable, flexible, and reusable[130].

Additionally, even if there were not a terrestrial shortage of materials like platinum group metals, there is no doubt that if we had more of them, it would usher in a new era of abundance on our planet. Imagine the advances in technology and quality of life that could be made if engineers could always use the ideal material for the job without having to worry about price or availability.

Finally, the successful mining of asteroids will be essential to the ultimate expansion of our species into the solar system and beyond. Launching heavy objects from the ground in to space makes much less sense than constructing those objects in space from available resources. These resources are all available in near-Earth bodies.

Thus, the value of mining asteroids for resources is clear. There are a number of sub-problems that must be solved in order to successfully accomplish such a mission[72]. Each of these problems can be solved elegantly with a combination of exponentially advancing technologies.

Remotely mining asteroids without the need for humans. Advances in AI and robotics will make this task cheaper and more efficient, and cheaper as robotics and microprocessors become cheaper.

Data Collection. Improved microprocessors, storage technology, and sensors will drop the price and enable more and better data to be collected.

Mass and performance of spacecraft. New materials such as carbon nanofibers and advanced composites will enable lighter structures to be as strong or stronger than steel.

Launch and Propulsion. Advances in launch (particularly beam-powered launch), solar technology, and energy storage will greatly increase the efficiency while decreasing the cost, dramatically cutting the costs of an asteroid mining mission.

Design. Advances in software modeling and design will dramatically increase the chance of success and decrease the cost of each mission.

Miniaturization. The smaller a mining vehicle is, the more can be launched per payload and the more fault-tolerant the entire overall mission can be. Many technologies are getting smaller every year, and this will dramatically affect the industry.

In sum, it is absolutely essential for humans to mine asteroids for materials, since Earth is running out of resources, it will be essential for building space-exploration machinery in place, it will usher in a new era of abundance on Earth, and the cost of mining space-based materials will soon be cheaper than mining those same materials terrestrially. By leveraging a key set of exponentially advancing technologies, it will for the first time be possible very shortly to mine asteroids effectively, efficiently, and profitably.

Space Based Solar Power

An underlying motive for all of human expansion has been the quest for energy. To early humans this meant the search for food, as food was the only form of energy they could take advantage of. Later on, our species created ways to harness other forms of energy through mechanical means—water power, wind power, coal, oil, uranium. These steady developments led to the expansion of the human race across the oceans to settle on nearly every habitual space on Earth.

Today, with a global power consumption of 12TW[127], we are reaching the end of the energy supplies we have come to use so commonly. It is expected that by the year 2020, the global power consumption will be nearly 20TW. It is becoming more expensive and more risky to search for fossil fuels to power our cities, and the combustion of these fuels is becoming highly damaging to the environment. Over 85% of the power used today comes from fossil fuels[127]. It is generally accepted that the time has come to focus on powering our world from completely renewable resources, and there are many resources that can be harnessed; tidal currents, wind, geothermal, and of course solar. Solar power is unquestionably the ultimate solution to our energy demands. In fact we have always relied on solar energy, we are just prefer to use it in it's stored form of a battery called fossil fuels.

When we begin to explore the possibility of harvesting energy in space, rather than terrestrially, we will create a world of energy beyond what we can imagine today. The amount of energy in space is far greater than that needed to sustain the population of the planet for decades to come. For instance, the kinetic energy in the solar wind is 10^{14} MW, or over a million times the current global power consumption. Collecting solar energy and transporting it to Earth will not only solve the energy problem, taking everyone out of the "dark age," but will also open the space frontier economically. As soon as the break-even point is passed, a viable business case for space energy production will swiftly drive down the costs of launch, as more and more capital comes in from the energy sector.

2.7 Space Science

"Somewhere, something incredible is waiting to be known"

– Carl Sagan

Before the 19th century, when the term "scientist" was first coined, people investigating Nature called themselves "Natural Philosophers" because they observed the workings of Nature and tried to extrapolate universal rules that would enable them to understand the surrounding World. What is the unit of life? What is the unit of matter? Is the Earth flat? These questions put forward by natural phylosophers, found an answer as technology started making its first steps into the era of modern science, thus empowering mankind to look deep into the structure of matter and far out beyond the atmosphere. As technology kept progressing exponentially, it allowed scientists to wander into new and unexplored territories. New questions thus arose: does life exist on other planets? Can intelligent life be found beyond our Solar System? Can there be different forms of intelligence? How did the Universe form? How did humankind evolve from prokaryotes? New fields—astrobiology, exobiology, planetary science, space-based astronomy—were born to answer these questions, while existing ones—biotechnology, medicine, neuroscience, synthetic biology—started just now extending their reach into outer space. Altogether, these disciplines fall under the umbrella of a new scientific era, that of Space Science.

The comparatively nascent field of Space Science is at the cusp of major growth, given the technologies available in the next decade. The same curiosity that has driven technology advancement and continuity over the past centuries on Earth, has lead scientists just beyond the atmosphere over the past decades and will, in the comparatively near future, bring humanity to explore and colonize outer space. Space Science will provide a parallel or a whole new domain of possibilities beyond our imaginations today. Importantly, it will bring about new paradigms for the Science that is done on Earth, out of the box thinking that could feed back into the living system with the potential of tackling many of the still unsolved or unsolvable problems. These underlying features inevitably set apart Space science from the rest of the modern sciences. One could say that today is the beginning of a new era in Science, an era in its own right, which will see its climax in the human colonization of other Earth-like planets and the exploration of other solar systems.

2.8 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.

3 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.

3.1 Nanotechnology and Materials Science

The first tools that humans used were simple sticks and stones, native "bulk" materials from the environment. Certain rocks were chosen for their hardness, or for their sharpness when cleaved, while certain sticks were used for their light weight and as tools requiring aspect ratios that are unattainable using rocks. Later these bulk materials were combined into things that enabled functions that were more than the sum of the parts, such as stone axes, animal traps, and wheeled vehicles.

In a similar way, we are barely beginning our technological evolution in space and are using many bulk materials, for example the planned Mars Curiosity rover is made mostly of aluminum and uses two-dimensional monolithic computation elements. The next step, and the goal of nanotechnology and materials science, is to discover the structural, electronic, thermal, and other physical properties of nanoscale materials and learn to harness these properties to create new or improved functionality, both structurally and on the scale of sensing and computation elements. These properties that may be inferior in bulk materials or perhaps not even exist on the macro-scale.

The enabling factors for continued improvement and innovation at the nanoscale reside in both funding new research and in an applications-centered, business-driven approach. They may reside in a shift from old ways of thinking and an agility to absorb new technologies as they become available.

3.2 Networks & Computing Systems

The exponential nature of Information Technologies and Networking is a well established phenomenon. In 1965, Intel's co-founder Gordon Moore noted that the number of components in integrated circuits had been doubling roughly every two years since their invention in 1958, and predicted that the doubling trend would continue for at least another decade. Since then, and more than forty years later, Moore's "law" continues to signal the evolution of processing speed, memory capacity, hard- disk storage, power consuption, transistor cost, and many other applicable metrics that seem to lay, roughly, on exponentially increasing (or decreasing) curves. (See Figure 6.)

It is remarkable that these exponential trends have survived many technology changes, and some technological paradigm shifts, without ralenting even through global crisis or other political and economical turmoils. An industry-wide belief in the nature of these exponentials has led companies to invest billions of dollars in the process of finding the next doubling factor before the competition, and drove many to describe Moore's law as the "self-fulfilling prophecy" of the electronics industry. However, and even though every few years new technical bottlenecks seem to suggest that Moore's Law might be getting to an end, our current understanding of the fundamental limits of computation shows that there is no fundamental reason why computational density should not keep increasing at its exponential pace for the forseeable future.

Over the last five decades, the exponential evolution of electronics has played a fundamental role in many of the scientific and technological achievements of humanity, and has been a fundamental enabler of global trade, the increased efficiency of value chains and the onset of what is called the knowledge economy. The Internet itself, still in its infancy, has revolutionized the way we do business, collaborate and interact with each other, and the same technology, in the hands of billions through mobile phones and its descendants, is predicted to play a fundamental role in integrating the next four billion people in the base of the pyramid to the global economy and to a global society. The astronomical increase in our capacity to generate, store and process information is leading fundamental changes in the way we think about and do science. Many other scientific disciplines, including, most notably, biology, are now increasingly becoming information sciences, and the exponential trends of information technologies spread to these disciplines and help put them in their own exponential paths.

We expect these trends to continue and evolve in the short term, and over the next few decades, to show an increasing paralellization of today's architectures, increasing interconnectedness, increasing miniaturization, new human-machine interfaces, new machine-to-machine interfaces, sensor and actuator networks; embedded computational systems in everyday objects; distributed, decentralized platforms for data acquisition, storage and processing; ubiquitous, high-bandwith networks; high-quality augmented/virtual reality with haptic interfaces; implantable bio-electronics; new computational paradigms for high-performance, massively parallel computation; new computational paradigms for energy-efficient and low heat computation.

At the same time, we expect Information Technologies, Computing Systems and Networks to impregnate, merge-into and drive the convergence of Biotechnology, Nanotechnology and Neurotechnology, to a new integrated technology realm at the nano-scale.

3.3 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 wil 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.

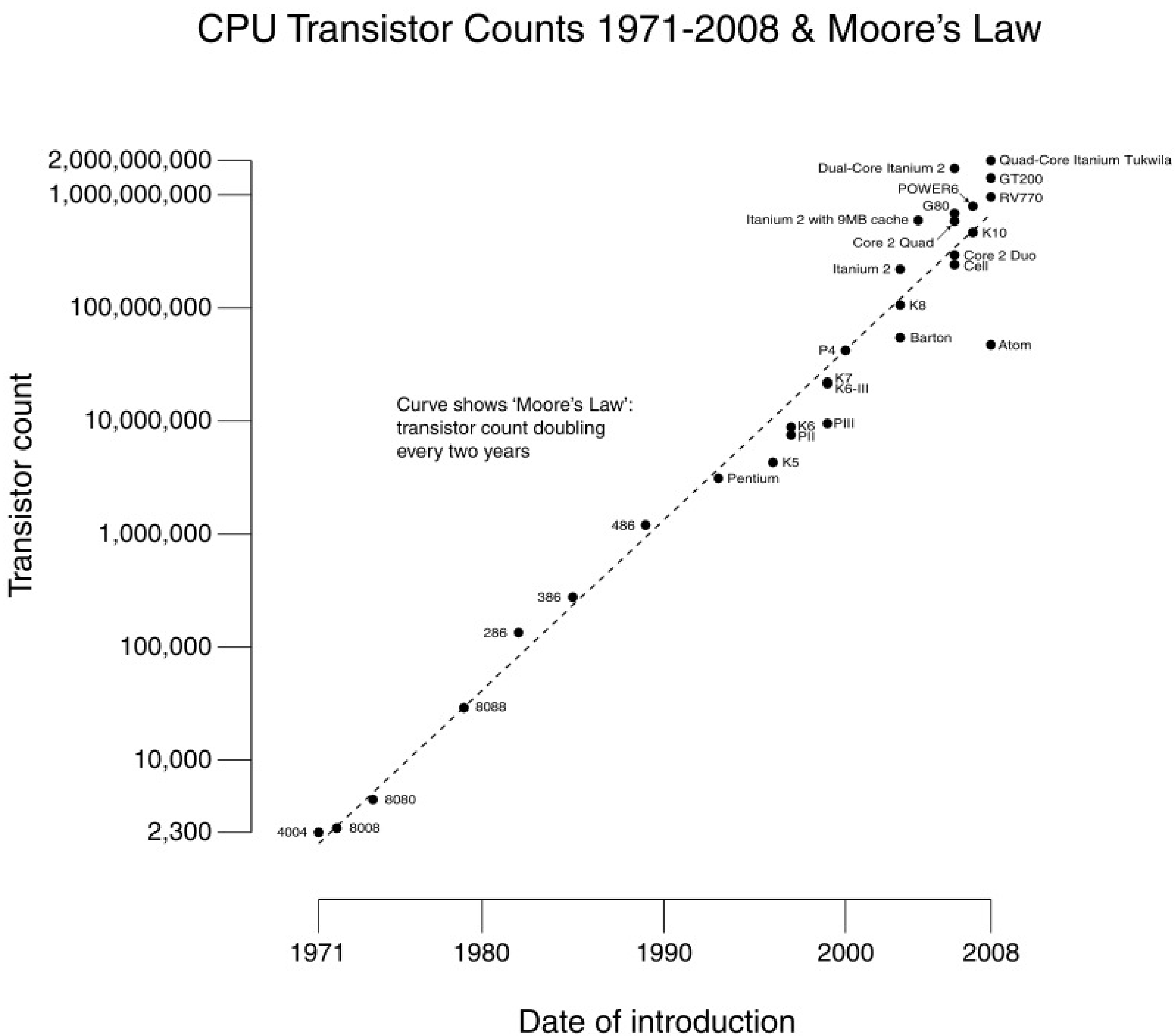

Figure 6. Transistor count and Moore's Law

3.4 Biotechnology

We currently live in the Renaissance era of Biology. Molecular biology along with computer science is the fastest growing science of the past four decades. This rapid development is due to a consecutive line of major milestones that include: Solving structure of the DNA, Deciphering the genetic code, Genetic engineering via restriction enzymes, The PCR machine, Microarry technology, The completion of the human genome project, microfluidics technology and more. The vast array of tools and knowledge gave rise to a growing branching of sub-fields of Molecular Biology that include Genetic engineering, Biophysics, Protein design, Protein fold prediction, Bioinformatics, Computational biology, Systems Biology and most recently, Synthetic Biology.

In the following paragraphs we shall outline the most notable exponentially growing molecular biology fields and methods:

Genomics is the extension of genetics to the scope of full organisms' genomes. Genomics is rapidly developing in the reading capabilities of DNA which is regarded as "DNA Sequencing," the artificial generation of DNA polymers which is regarded as "DNA synthesis" and the comprehension of the genetic information.

DNA Sequencing capability is exponentially improving ever since the human genome project was launched. The first significant technological leap is owed to the contribution of Dr. Craig Venters that introduced the "Shotgun" method through his company Celera. An active and highly innovative industry competes by introducing diverse technologies for sequencing which may be very different in method. Although there still is no one technological golden standard, the speed of sequencing and amount of DNA material that can be processed in parallel is exponentially growing whereas the price is rapidly dropping. This could be exemplified by the amount of DNA sequences submitted to Genbank, a NIH funded DNA repository (see figure).

The vast amount of genetically available material paved the way for the Bioinformatics fields that was essential for the assembly, interpretation and pattern recognition of the accumulated data. Bioinformatics in turn grow rapidly and branched into several sub fields that specializes in genes ("coding regions"), regulatory elements ("intergenic regions"), gene expression analysis, systems biology and computational biology. Systems biology that aims to achieve the co-functioning comprehension of a large set of genes and proteins is rapidly growing as can be seen by the amount of grant funds the field receives (see figure).

Upon the completion of the human genome project in 2000 by both by the international consortium and the Celera private venture the tipping point and rise of the post-genomic era began. The draft to our genetic software was accessible to study for the first time in human history, and genes where being studied in large sets of thousands rather than one at a time. A similar era is about to embark soon, as full genome sequencing prices will fall sufficiently to enable a multi-genome era where humanity will hold a large set a genomes by different individuals, enabling comparative genomics, the exhaustive comparison of entire genomes.

DNA synthesis capability, albeit lagging behind the DNA sequencing technology, is also advancing by a verity of methods, and synthetic DNA grows longer and cheaper rapidly. As in the DNA sequencing arena, Dr. Craig Venters contributed greatly to this field to and currently holds the record for the largest sequences of artificially generated DNA. Long synthesized DNA is driving the emerging field of synthetic biology that aims to fabricate novel life forms. The current state of the art is a partial generation of a bacterial organism.

Proteomics is the extension of Biochemistry to the scope of full organisms' proteins. Proteomics is rapidly developing in the reading capabilities to solve the 3D structure of proteins by means of X-ray crystallization and NMR studies as can be seen by the exponentially accumulation of protein structures in PDB, the protein data bank (see figure). Although the 3D structure of most proteins is known to be directed by the amino acid sequence of the proteins, the question of inferring the structure from the sequence which is also known as "the protein folding problem" is still largely unsolved and is on of Biology's holy grails. However, the computational prediction of the structures are growing increasingly better due to superior heuristics, vast amount of biological raw data and extended computation capabilities, and it is widely believed this challenge will be eventually solved. The ability to comprehend the correlation of protein structure and function will enable the rational protein design and will open a virtually limitless space of synthetic proteins with properties that to date do not exist in nature. A mature protein design field could correct for most genetic defects along with the transplantation of genes via Gene therapy methods, create new genes and produce new bio materials and biological drugs such as hormones and antibodies. To date, protein design is limited to semi-random in vitro evolution methods, partially driven by rational thought and by chimerical approaches of modular construction of proteins based on naturally existing scaffolds.

The microarray technology and its subset DNA-chips is yet another disruptive trend in biology that enables a vast readout of all the expressed genes within a cell by assessing the presence of mRNA transcripts. This technology, along with the exponential advances in DNA sequencing, greatly contributed to the generation of the Bioinformatics field, and to its sub branches, gene expression regulation and Systems biology. The microarrays that were at first extremely expensive, unreliable and with a relatively small number of biomarkers, are now commonly used, as can be seen in the elevated number of publications that address microarray data, and they are rapidly growing cheaper, larger and robust. To date there is still no gold standard to the optimal mathematical correction algorithm for their analysis, and the field of microarray analysis quite active.

Another disruptive and rather new technology is Microfluidics that enables micro manipulation and experimentation on single cells via liquidous apparatus with miniature compartments. Microfluidics enables experimentations that have previously not been feasible.

In the near future, we will be readily reading, generating, transplanting, manipulating and creating genetic and protein material, capability that will enable us to reshape life forms including humans.

3.5 Neurotechnology and Medicine

The human beings through research and technology have begun to understand the nature and mysteries of the Universe. However, Space is a harsh environment, and technological advancements in material science, robotics, power generation, and medical equipment will be required to ensure that astronauts survive interplanetary journeys and settlements. In addition, operational challenges, such as the management of life-support systems, food and nutrition, medical care, and psychosocial health due to long-term confinement, will have an impact on human health during long-term space missions and more even if we think to settle and to stay on other planets or regions in our Solar System.

Since the human is considered to be a critical system of space flight in the same way the propulsion, thermal, and power are critical systems to space flight, the searching of opportunities where accelerating technologies could be possible solutions in these issues in the coming future, is warranted.

Why go into space when we have so many problems here on Earth? It is a legitimate question as unfortunately not enough people have been made aware of the vast benefits the space program provides that increase the quality of our daily lives. Applications on Earth of technology needed for space flight have produced thousands of “spinoffs” that contribute to improving several fields including medicine, biotechnology, and neurosciences[143]. One small example is the Hubble Space Telescope technology which was used in the Charge Coupled Device (CCD) chips for digital imaging breast biopsies. The resulting device images breast tissue more clearly and efficiently than other existing technologies. The CCD chips are so advanced that they can detect the minute differences between a malignant or benign tumor without the need for a surgical biopsy. With over 500,000 women needing biopsies, this technology saves time and money for this procedure versus surgical biopsy.

At the same time, accelerating technologies in medicine and neuroscience should help to solve huge problems in human space exploration and “staying there,” including better methods and techniques in the basic and clinical research, which are the basis for new knowledge and the source for new technologies.

Medicine tools that could help solving grand challenges are immersing in biotechnology, nanomedicine and nanomaterials, robotic, artificial intelligence, bio-engineering, and bio-informatics. More specifically, the broad spectrum of sensors and biotech for prevention, and early diagnosis of the health problems, new materials for radiation protection, autonomous medical care (AI, robotics, bioinformatics) for diagnosis and treatment, and tissue engineering for recovery, are some interesting examples where exponential technologies should be involved.

Neuroscience research helps us to describe and understand how the brain controls behavior. One of the critical tools is the recording equipment which helps us to study the neural signals during behavior. While noninvasive neural signal recording techniques, such as electroencephalography (EEG) and functional magnetic resonance imaging (fMRI), are getting more precise and easier to operate, their costs are also dropping [51]. As these equipments are more affordable for the public, more neural recordings from individuals are available to study a wide range of problems. The exponential increase in hardware and software tools and the available data help the development of statistical models for different medical applications, such as personal health diagnostics.

Another trend observed is the decrease in computational time for non-invasive medical diagnosis through computer tomography (CT), MRI and positron emission tomography (PET) as the computational power exponentially increases through techniques like parallelization. Meanwhile, for instance, PET detectors are getting smaller at an even faster rate, offering higher resolution data [97]. Figure 7 shows that improvements in run time alone are not sufficient to meet the computing demands for future PET scanners.

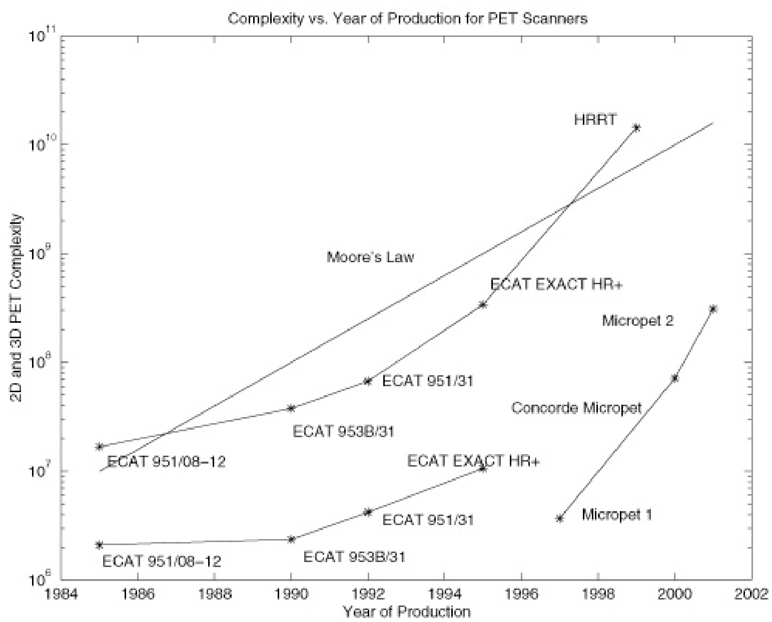

Figure 7. Illustration of the approximate order of computational complexity for 2D and 3D clinical and small animal scanners shown in comparisons to “Moore’s law”, the observation that single-processor computing power doubles roughly every 18 months [97]. The lower curve for the ECAT systems represents 2D complexity, the upper curve represents 3D complexity.

Significant improvements can be also found in neural prosthetic devices. Using implanted electrodes to deliver electrical stimulation to the sensory nervous system, cochlear implants have been well developed for the deaf to hear and retinal implants are under FDA trials for the blind to see. Figure 8 from [157] demonstrated the improvement of sentence recognition of cochlear-implant users with more recent models. Custom motor prosthetics like robotic arms with high dexterity are developed for patients who lost their limbs. Paralyzed patients can now interact with the world with brain computer interface (BCI). The exponential increase in computational power also allows researchers to simulate large neuronal network and the resulting knowledge benefits the development of better neural prosthetic devices.

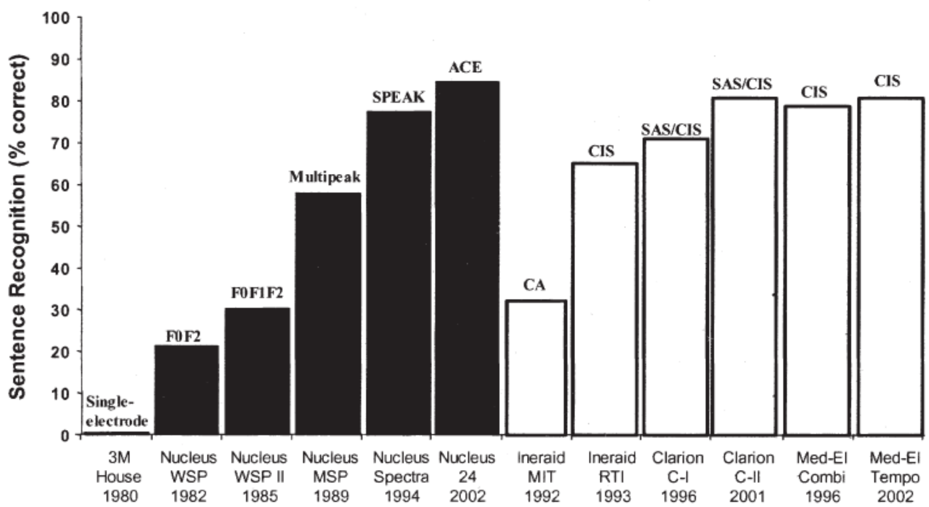

Figure 8. Sentence recognition of cochlear-implant users [157]. The x-axis labels show the type of device, the processor model, the place where the study was conducted, and the year the study was published. The y-axis shows percent correct scores for sentence recognition in quiet. The scores in cochlear implants developed before 1994 were averaged from investigated studies published in peer-reviewed journals. The score in devices developed thereafter were obtained from company-sponsored clinical trials that had also been published in peer-reviewed journals. Besides "single-electrode" for the 3M/House device, the text on top of the bars represent speech processing strategies including SPEAK (Spectral PEAK extraction), ACE (Advanced Combination Encoder), CA (Compressed Analog), CIS (Continuous Interleaved Sampler), and SAS (Simultaneous Analog Stimulation).

4 Exponential Technology Opportunities

In this section we discuss a number of opportunities we have collectively identified in the intersection of the exponential technologies described in section 3 with the problem spaces discussed in section 2. We have organized these opportunities on a rough timeline of when the underlying technology trends may enable them. For each opportunity, we briefly describe the exact **Application**, the **Problem** being solved, the **Opportunity** to solve it, and with which **Exponential Technologies**, the **Problem Spaces** it addresses, **Other Connected Ideas**, an **Estimate of the Potential Benefit**, a list of **Who is Doing It Now**, the approximate **Time Scale**, **Convergences** with other ideas, and the most **Significant Bottlenecks**.

Contents of this Section

4.1 10-year Time Horizon

4.1.1 Cheap Spacecraft for Developing Nations

Application: Use cheap spacecraft as a way to enable developing countries to get involved in space.

Problem: Third world countries are cut off from technology and science in many ways, and often the general public in such countries don't understand what space is and Earth is just a small part of a larger universe.

Opportunity: Imagine the headlines: Ethopia launches their own satellite.If we give developing countries the tools to build and launch their own *u*seful satellite at a low-cost (via increasing capabilities of satellites and dramatic reduction in cost), we can:

(a) get 3rd-world countries more involved in space and give them a greater understanding of the world we live in

(b) Show the world that space is opening up to all people, and becoming increasingly cheaper to get involved.

Enabling technologies: The increase in computational power and decrease in cost is enabling satellites to be built at fractions of the current cost.

Who is doing it:

(a) Chris Boshuizen and a team of NASA Ames Research Center engineers launched two Nexus One cellphones to 30,000 feet in July 2010, with plans to launch them to orbit in 2011 [108].

(b) Bob Twiggs, inventor of the CubeSat, is working on launching eight "pocket CubeSats" into orbit in 2011. The cubes are an eighth of the volume of standard CubeSats at roughly 5 centimeters, and are expected to cost less than $25,000 each with full capabilities [116].

Time Scale: The materials and parts to launch a satellite for less than $10,000 and eventually $1,000 is approaching over the next five to ten years [116].

Significant Bottlenecks: The largest bottleneck isn't the technology. Rather, it's the ability to acquire philanthropic funds for developing countries. Since most countries in Africa don't have the money for clean water or sustainable energy, this idea would have to be sold to philanthropists as a means to educate people in a way that enables them to build their own economy and future space program.

4.1.2 DIY Spacecraft

Application: Build a satellite architecture that is on the order of hundreds of dollars to launch. Allows for individuals to own and operate their own missions.

Problem: Creating the business case. Creating the communication system to control and send/receive data from the space crafts.

Opportunity: With current technology a satellite can be made to sizes within 10 cm on a side and costing the price of a personal computer. With the advancements in nanotechnology, computing, and AI/robotics these spacecrafts will continue to shrink exponentially in size. If we can launch 1000s of these in one rocket the cost per satellite becomes very low.

Each launch will release a swarm of satellites that can serve many purposes. First, because each satellite is identical, all that needs to change to change its mission is the software program, which can be uploaded from ground. This means individuals can own or rent a satellite or any part of the swarm to operate their individual mission, that they create of find through open source software sharing. Monitor global warming from your desktop live, create science fair or research projects, take your own "pale blue dot" picture. Google may decide to buy or rent an entire swarm and take Google Earth live giving users incredible benefits such as Instant disaster relief monitoring, The best ideas are the ones that haven't been though of yet.This idea WILL open the space frontier to everyone on Earth.

Estimate of the Potential Benefit: This technology will be the next best thing to actually putting people in space. It will allow them to see space through their own eyes, which could in turn help motivate the opening of the space frontier.

Who is doing it: NASA Ames team (Chris Boshuizen, Matthew Reyes, William Marshall), many university Cubesat groups.

4.1.3 Open Source Cube Satellites

Application: Open source/open cube satellites for development (OSCS)

Problem: Developing countries more often than not have no direct access to satellites and little influence on application development, such as remote sensing, communication, and science.

Opportunity: OSCS can provide a new platform for developing countries to improve data analytics for development. On open source/open access model is apt to spark innovation in areas such as remote sensing for pandemics, resource identification, communication, education, engineering, etc. [138]

Exponential Technologies: Nanotechnology, Computing, and/or Networks.

Grand Challenges: Getting There, Space Science

Other Connected Ideas: Intelligent Space Operating System (ISOS)

Estimate of the Potential Benefit: Significant benefit for developing countries if combined with terrestrial communication systems. Financing can be achieved through Worldbank and NGO's with the benefit that loans/donations are transparent (Satellite/infrastructure).

Who is doing it:

(a) NASA

(b) ESA

(c) JAXA

(d) MIT

Time Scale: Immediately, increasingly cheaper in future

Convergence: Nanotechology

Significant Bottlenecks: Cheap Access to Space

4.1.4 Intelligent Space Operating System

Application: Intelligent Space Operating System (ISOS)

Problem: Robotics, AI and communication systems for space more often than not are designed in isolated fashion. Hence devices and data transmission is mostly non-interoperable, isolated with great redundancies.

Opportunity: An Intelligent Space Operating System provides an open ecosystem for AI, communication systems and satellites, as well as robotics to tie in by means of standardized API's. Parts of such ISOS can be open-source and reconfigurable. Open access, open purpose, is granted as much as possible. AN ISOS ideally encompasses all technology within space and provides unique identifiers (IPs with encrypted authentication for safety/privacy). Similar to the earthbound internet (of things) the ISOS provides connectivity, packet switching and intermittent storage, smart communication processes and optimal routing, satellite access, swarm satellite tie-in, spacecraft and extraterrestrial station communication, inter and intra-stellar communications, earthbound internet access and geo-stational satellites, real-time as well as time- buffered information transmission, and inter-robotic communication.

Exponential Technologies: Nanotechnology (Microsatellites), Computing Networks, Laser technology, Solar Panels/energy

Grand Challenges: Robotic Exploration/ Communication & Information Networks

Estimate of the Potential Benefit: Eradication of redundancies, standardization, smart information transmission.

Who is doing it:

(a) Google

(b) NASA

(c) ESA

(d) JAXA

Time Scale: Incremental growth during the next years, inclining growth with evolution of microsatellites, exponential growth as soon as cheap access is possible.

Convergence: nanotech

Significant Bottlenecks: cheap access to space, but not essential

4.1.5 Intelligent Environments for Colonization

Application: -

Problem: Extraterrestrial habitats for human space exploration must provide a high level of sensing capabilities to assure life support. If humans are out to colonize space, long term needs for human, animal and plant survival must be met.

Opportunity: Smart environments are already emerging on earth. Due to innovation in sensor networks, sensor sophistication and miniaturization, an increasing amount of environmental conditions can be assessed. Sophisticated data analysis techniques allow for better modeling of conditions and actions to be undertaken. Smart environments such as a planetary or orbital station can connect to other nodes within the Intelligent Space Operating Systems (see subsubsection 4.1.4) for optimization of the overall space system state.

Exponential Technologies: Nanotechnology, Biotechnology, Computing, Networks.

Grand Challenges: Habitats, biospheres, networks and communication.

Other Connected Ideas: ISOS (Intelligent Space Operating Systems)

Estimate of the Potential Benefit: Essential for survival and colonization, interconnectivity with other habitation nodes allows for overall system optimization.

Who is doing it:

(a) NASA

(b) Living-Planit

(c) Smart cities MIT

(d) Responsive environments group MIT

Time Scale: 5-10 years.

Convergence: Nanotech and exponential ICT. Sensor development and miniaturization.

4.1.6 Microbial Fuel Cells

Application: The use of microbial fuel cells to generate power within the Life Support Systems and any different energetic applications in spaceflight or planetary stations could be a suitable, renewable and efficient way of produce removable energy.

Problem: The energy use for life support systems and other applications during spaceflight and space station are restricted to functions previously planned. The use of additional energy system could help in building successful new life support systems and closed loop systems.

Opportunity: Microbial Fuel Cells (MFC)s are devices that use bacteria as the catalysts to oxidize organic and inorganic matter and generate current [121] . Electrons produced by the bacteria from these substrates are transferred to the anode (negative terminal) and flow to the cathode (positive terminal) linked by a conductive material containing a resistor, or operated under a load (i.e., producing electricity that runs a device). The construction and analysis of MFCs requires knowledge of different scientific and engineering fields, ranging from microbiology and electrochemistry to materials and environmental engineering. For example, was observed that when a water-soluble distyrylstilbene oligoelectrolyte (DSSN+) was added into bioreactors, these molecules were preferentially accumulate within cell membranes and were used as the electron transport mediator increasing the MFCs performance [68]. In addition, Yuan et al. reported a novel bioelectrochemical system to effectively reduce organic pollutant with utilization of the energy derived from a microbial fuel cell [156]. In such a system, there is a synergetic effect between the electrochemical and photocatalytic oxidation processes. Both systems show great potential to produce energy and to be part of a closed loop system for space exploration.

Exponential Technologies: Biotechnology, Synthetic biology.

Grand Challenges: Human exploration (staying there, life support systems)

Other Connected Ideas: Closed loop systems, bioconductors

Estimate of the Potential Benefit: A better source of energy which can be used in space propulsion and activation of improved life support systems.

Who is doing it:

(a) Dr. Bruce E. Logan Hydrogen Energy Center, 212 Sackett Building, Penn State University, University Park, Pennsylvania

(b) Dr. Shi-Jie Yuan, Department of Chemistry, University of Science & Technology of China, Hefei, 230026, China

(c) Dr. Korneel Rabaey, and Dr. Jeffrey M. Foley, Advanced Water Management Centre, Gehrmann Building, The University of Queensland, Brisbane, Queensland 4072, Australia

Time Scale: 5 years

Convergence: Being in the area of bioreactors, this technology could benefit big challenges in up-cycle and energy areas.

Significant Bottlenecks: MFC research is a rapidly evolving field that lacks established terminology and methods for the analysis of system performance. This makes it difficult for researchers to compare devices on an equivalent basis. The most of MFCs require large volumes to produce more energy which is a problem in launch costs.

4.1.7 Polyethelyne/Biopolymer Radiation Shield

Application: Generation of hydrogen rich polymers to shield the inside of shuttles/inflatable inhabitable units from ionizing particle and high energy electromagnetic radiation

Problem: The Earth's magnetosphere prevents protons, electrons and heavier nuclei that are continuously ejected by the Sun from reaching the soil. Also, Earth's atmosphere blocks some of the visible and infrared electromagnetic radiation, almost all the ultraviolet and all the X and gamma rays. While humans have evolved a system of UV protection involving melanin, no shielding is naturally provided from particle radiation.

Human exploration and colonization, as well as orbiting astronauts and satellites in the shorter term, will greatly depend on the advances in radiation protection technology, since the planets/moons/asteroids that we will be in reach of most probably will not have an inherent magnetosphere that will protect us.

Especially dangerous are the flares and coronal mass ejections generated by the Sun in an observed nonstationary Poisson process, i.e. random distribution [20]. These particles have sufficient energy to get through any shielding material currently used in space shuttles/space suits as well as the Earth's magnetosphere and because they are unpredictable they constitute a major threat. [6]

Importantly, the use of improper shielding material might cause the generation of secondary radiation, i.e. acceleration of a charged particle through deflection of another charged particle, which increases the probability of absorption from the organism [1]. It is therefore vital that complete ionizing radiation protection be established before any human colonization missions.

Opportunity: It has been observed that shielding materials of low atomic number, such as hydrogen, are more effective against cosmic radiation (high energy particle radiation from outer space) than, say, aluminum, because they reduce the production of secondary radiation particles [20]. This can be extended to other ionizing high energy particle radiation brought by the Sun. Polyethylene, because of its hydrogenous nature, has been extensively used for shielding of crew quarters on board of the ISS. If this system were to be united to the upcycling of the hydrogen used to power the hydrogen-based external propulsion engine proposed in this ETIR report in the "Getting There" problem space, as well as the upcycling of waste water inherently produced in the system, greater achievements might be introduced in the travelling phase. In order to establish a shielding system for optimal colonization of other planets, research in the realm of synthetic biology might lead us to the engineering of microrgnisms that can produce highly hydrogenous biopolymers or the duration of our stay.

Exponential Technologies: nanotechnology, biotechnology

Grand Challenges: Getting There, Staying There

Other Connected Ideas: Ability to prediction solar flares and coronal mass ejections ahead of bursts would enable for preventive measures to be taken in time for reinforcement of protection.

Estimate of the Potential Benefit: Complete radiation protection would enable for a better quality of life on other planets

Who is doing it:

(a) Shavers Laboratories at NASA Langley Research Center (Hampton) and NASA Johnson Space Center (Houston)

(b) Aschwanden laboratories at Lockheed Martin Advanced Technology Center, Solar & Astrophysics Laboratory (Palo Alto, CA) and McTiernan laboratories at Space Sciences Laboratory, University of California, Berkeley

Time Scale: 20 years

Convergence: External propulsion engine, water upcycling on space shuttles and synthetic biology for microbial engineering

Significant Bottlenecks: There is no unique solution. Different approaches must be taken to make different legs of the journey possible. Ideally, there would be one shielding material everything would be made of.

4.1.8 Protein Engineering for Drug Design

Application: X-ray Crystallography and electron Crystallography in space can be used to obtain higher quality 3D and 2D crystals, respectively, of proteins engineered for specific drug target interaction.

Problem: Protein Crystallography is a science in its own right. The process of making a crystal is laborious and the protocol not automatable as it is slightly different for each protein. Not only, the same method cannot be deployed for soluble and insoluble (or membrane) proteins since the types of crystals that they generate are different. On average only one over ten proteins yields crystals suitable for structure determination [146].

Opportunity: Increasing the success rate of protein Crystallography using space.

Exponential Technologies: X-ray Crystallography, Transmission Electron Microscope

Grand Challenges: Human exploration

Other Connected Ideas: Having crystallisation facilities on board of a space shuttle or space station will enable the analysis of any molecule whose atoms can be arranged in solids. Asteroid composition as well as planet soil compositions can be analysed this way, by sampling first, crystallizing and then imaging.

Estimate of the Potential Benefit:

Who is doing it:

(a) Zagari laboratories at the University of Naples "Federico II"

(b) Dr. Julio Valdivia Silva's laboratories

Time Scale: 5 years

Convergence: Advances in X-ray and electron Crystallography technologies will make the production of high quality crystals less fundamental for the generation of a high quality image. Also, methods such as fiber diffraction, powder diffraction and small-angle X-ray scattering are all technologies that are deployed as an alternative to X-ray and electron Crystallography for the production of lower resolution images, but will grow exponentially over the next ten years and will become just as good options to X-ray and electron Crystallography.

Significant Bottlenecks: Crystal production, especially for membrane (insoluble) proteins. Advances in X-ray and electron Crystallography technologies might result

4.1.9 Genome Sequencing/Microarrays for Detection of Cancer Progression

Application: Understanding the underlying principle by which "apoptosis," or programmed cell death, is re-activated in cancer cells in the absence of gravity (simulated microgravity) and use this knowledge to tackle cancer progression on Earth.

Problem: Cancer is a relentless enemy that has yet to be defeated. One in every eight deaths worldwide is caused by cancer [19]. Finding a cure has proven challenging mostly because there is a basic lack of understanding into the molecular mechanisms underlying the disease.

Opportunity: Culturing cancer cells in simulated micro-gravity with the Rotating Wall Vessel (RWV) has given us insights into the chance that an environment lacking gravity might re-activate apoptosis mechanisms within cells [75]. "Apoptosis" is a term used in biology to indicate a mechanism of programmed cell death that is essential to ensure the balanced turn over of cells within healthy tissues. If switched off, as happens in most cancer types, the cells are enabled to proliferate indefinitely, eventually invading other tissues creating metastasis and causing the death of the patient. Understanding the mechanisms by which re-activation of apoptosis occurs in microgravity, we might be able to apply these to cancer cells back on Earth and produce similar results. In vivo results have been achieved in D. melanogaster (fruit fly) experiments, in which a cohort of flies carrying spontaneous tumors was flown into space for one generation (20 days) and upon their return showed a completely reverted phenotype, that is, the tumors were absent [60].

Exponential Technologies: Biotechnology

Grand Challenges: Gravity is one of the fundamental and universal physical parameters on Earth. Therefore, one critical scientific question is how much are organisms affected by changes in gravity and how does the answer to this question affect human space exploration and colonization?

Other Connected Ideas: Heart Conditions, Parkinson's Disease, Alzheimer's Disease

Estimate of the Potential Benefit: Possible insights into a cure to cancer

Who is doing it:

(a) Elizabeth Bladder laboratories, Australian Centre for Astrobiology, University of New South Wales, Sydney, Australia

(b) Augusto Coccoli's group in Germany at the University of Berlin

Time Scale: 5 years

Convergence: AI/robotics to ensure automatic manipulation of life support systems for in vivo validation experiments in mice, which will be fundamental for the proof of principle. Also, as nanotechnology hits the knee of the curve, the fast and efficient delivery of vectors carrying a possible cure - such as DNA sequences made to replace existing damaged ones - will be made possible. An increase in the efficacy of simulated microgravity devices will allow for experiments to be conducted with a better degree of accuracy on Earth.

Significant Bottlenecks: Simulated microgravity is not a perfect model for zero gravity, as shown in the studies by Julio Valdiva and others, in which the gene expression pattern of the same cell culture in microgravity and space showed poor correlation.

4.1.10 Space Standardization

Application: Create standards for software, hardware, and communication in space.

Problem: The space community is poised at a similar position to the position of computer users when there were only a handful of computers in the world. Every space mission we make is different and independent. The physical connectivity of the earliest networks such as Advanced Research Projects Agency Network (ARPANET), and the data connectivity enabled by standardisation of communication protocols, enabled the internet technology explosion we still enjoy today. We are in a similar position in space now, barely wetting our toes on the cosmic ocean, needing to begin to prepare for the voyage ahead.

Opportunity: The time has come to develop hardware, software, and communications standards that enable a distributed communications and functional network in space. This will inspire new innovations in space (similar to creating the internet protocols and letting the "Youtubes" and "Amazons" develop). We would ideally not need to force anyone to adopt this model, but rather by simply connecting to this network and using the same protocols the user is granted huge benefits of not needing to develop certain components themselves.

This is not a business model any more than Vint Cerf Cerf's standardization of internet protocols was a revenue source. However we could create specific businesses and release them in tandem with this idea, showing the possibilities without limiting the standardization structure to any given business model. In a sense this tandem approach comprises opening the floodgates and riding the wave out.

Exponential Technologies: This can be viewed as an enabler of exponential technologies of the future.

Grand Challenges: Getting There, Staying There, Human Exploration, Robotic Exploration

Estimate of the Potential Benefit: As humanity spreads into the solar system, this will be both an extension of the internet (and just as indispensible), and a framework for hardware and software that accelerates and innovates growth. For example, we may start with swarm satellites around earth that have standard positioning and intercommunications protocols. Then we have swarm satellites around Mars (the "flies"). Then we have many autonomous builder robots that create human habitats on mars (the "ants"), and the fact that the "ants" and "flies" are distributed systems that speak the same language and talk about their relative and absolute positions, etc, in the same way, enables quick creation and design iteration.

Who is doing it: Vint Cerf is working with Jet Propulsion Laboratory (JPL) on the Interplanetary Internet, and NASA has repurposed some of their spacecraft for communication for more modern missions (1). However if the early internet was forced to grow by repurposing, retrofitting, and reverse engineering each computer whenever you add a new one, it would not enable the explosive internet phenomenon we see today. This is currently mission-by-mission and is not on a large scale.

Time Scale: The first versions of these standards can be released in 1-2 years, in tandem with flexible pico-satellite businesses. However just like internet protocols these standards need to be rigid enough to be useful, yet organic enough to be able to adapt to changing needs.

Convergence:

Significant Bottlenecks: Monetary. Rather than creating the YouTube or the Amazon of space, we'd be creating the Internet of space, upon which other successes ride. Without tandem applications, this could be a huge bottleneck.

[2]

4.1.11 Swarm Satellites

Application: A Swarm of Satellites in Low Earth Orbit (LEO) provide a "plug-and-play" platform for space-based applications.

Problem: Providing space-based services to earth requires today a huge investment in infrastructure, and space-based services are therefore either very expensive or restricted to those with very massive markets.

Opportunity: A cloud of micro-satellites positioned as a distributed, open platform for the creation of space-based applications in radar imaging and communications can revolutionize the way we think about building space-based services and applications. Initially in LEO, a cloud like this could expand to support our colonization and exploration efforts in the solar system.

Exponential Technologies: Computing, Networks, AI, Robotics

Grand Challenges: Getting There, Staying There

Other Connected Ideas: Swarms of robots on the moon, swarms of asteroid-prospecting / asteroid-mining robots; nano/femtosatellites; satellite-on-a-phone;

Estimate of the Potential Benefit: New, low-cost, very targeted space-based services can affect positively the lives of billions. The current Commercial Satellites/Services market is a 160 Billion dollars a year market (including mass-marketed services such as Satellite TV and GPS services), the availability of a platform like the one we suggest has the potential to revolutionize this market, helping it grow by an order of magnitud. Also, we predict that the ability to create space-based applications without fixed infrastructure cost will have the biggest effect in developing countries/economies, both for communications and as a tool to leverage agriculture, fishing, primary goods extraction and processing, disaster monitoring and emergency response.

Who is doing it:

(a) The Technology Satellite of the 21st Century (Techsat21) Project attempted to launch a spaceborne sparse array for radar, but was cancelled.

(b) Cubesats are open-source micro-satellites being built by universities and small companies.

(c) DARPA is funding a "Fractionated Spacecraft" program, attempting to create a inter-communicating sparse array of spacecraft. The second phase of the program was awarded to Orbital Sciences, along with IBM and JPL, in December 2009.

Time Scale: This platform can be built today.

Convergence: This technologies will be able to benefit in the future from advances in Nano-Materials for energy harvesting and storage; also, the concept would benefit greatly from cheap launch

Significant Bottlenecks:

(a) Precise Positioning in orbit for the purposes of Sparse Phased-Arrays for Radar requires the development of new algorithms that leverage the collective of the swarm to increase definition.

(b) Space Debris is an important problem, and although the micro-satellites will de-orbit naturally in the course of a few years, doubling the number of active satellites in orbit requires significant study.

4.1.12 Supercomputers in Space

Application: Data centers and supercomputers in space stations.

Problem: Time lag between Earth and the sent missions, too much data is lost because it has not been captured the moment it happened, future missions to further planets would be difficult if there's not a base station that can communicate, receive and send information directly.

Opportunity: Lots of data can be gathered and detected from space (Temperature variations, radiation, cosmic rays, etc.). Different simulations can be done efficiently in space, and direct communication can be achieved between future robotic exploration missions and the base space stations.

Grand Challenges: Staying there, human exploration, robot exploration

Other Connected Ideas: Computing, memory, programming, processing power, strong AI, narrow AI

Estimate of the Potential Benefit:

Who is doing it:

Time Scale: 10-20 years

Convergence: Artificial general intelligence (AGI), Narrow AI, Computation, Transistors, Quantum Computation, Memory, Solar Power, processing power

Significant Bottlenecks: Computation power, Launching, Cost, Maintenance, Politics, AI

4.1.13 CAD with Space Physics Simulation

Application: A space version of Computer-Aided Design (CAD)/multiphysics with space-physics simulation (microgravity, radiation, insulation, vacuum sealing, etc.)

Problem: Reduce product development cycles by reducing time to design and test spacecraft, tools, technologies and habitat designs.

Opportunity: Standardize a platform for rapid design and prototyping for commercial space, research and education.

Exponential Technologies: AI, Robotics, Computing and Networks.

Grand Challenges: Getting There, Staying There

Other Connected Ideas: 3D printing in-space

Who is doing it: To some extent, Ansys and Autodesk, but a specific space engineering product or profile does not exist today.

Time Scale: <5 years

4.1.14 Radiator / Nanotube Arranged in a "Forest"

Application: Generating electricity, or controlling temperature in space can depend on the thermal properties of radiators.

Problem: Radiators can be large, heavy, or their properities can be degraded by contamination.

Opportunity: Single-Walled Carbon Nanotubes (SWCNT), arranged in a "forest" have very high absorptivity to light and other electromagnetic radiation, and very good thermal conductive properties. This could reduce the size of or increase the performance of existing radiators. Bucky paper [148, 3, 149] represents a form of material currently in production that could serve this role.

Exponential Technologies: Nanotechnology

Grand Challenges: Robotic Exploration, Staying There

Other Connected Ideas: Structural nanomaterials, nanotubes, graphene

Estimate of the Potential Benefit: As a thermal conductor: Graphitic materials such as nanotubes have up to an order of magnitude better thermal conductivity than silver (the metal with the highest thermal conductivity), allowing fast dissipation of heat. As an absorber: Current black paints have absorptivities of about 0.94 [5], but SWCNT have absorptivity up to 0.99, which may be useful for example on baffles on the insides of space telescopes to absorb stray light.

Who is doing it:

(a) Scientists Harold Kroto from the University of Sussex, and Robert Curl Jr. and Richard Smalley from Rice University shared the 1996 Noble Prize in Chemistry for their work on fullerenes.

(b) The Florida Advanced Center for Composite Technologies (FACCT or FAC2T) directed by Ben Wang, Professor of Industrial Engineering at the Florida A&M University-FSU College of Engineering, have carried out pioneering research on the properties, bulk manufacture, integration into nanocomposites, and applications of 'buckypaper' since the year 2000, when Dr. Wang was first introduced to it. [5]

(c) Tsinghua-Foxconn Nanotechnology Research Center and Department of Physics, Tsinghua University, Beijing 100084, People's Republic of China [148]

(d) Arguably the world's most renoun expert on large-scale nanotube ribbons, formed from drawing and weaving nanotubes, is Ray Baughman at the Nanotech Institute at UT-Dallas. He pioneered a technique to make carbon nanotube sheets and yarns [4]

(e) However carbon nanotubes are fragile and often must be embedded in a polymer or ceramic matrix. Pioneers of nanotube-embedded ceramics include Robert Davis [39] and Pulickel Ajayan [87], and Eric A. Verploegen for nanotube-embedded polymers.

Time Scale: These materials have been produced in the laboratory for several years, and are even available for purchase [3]. It appears that they may be ready for a demonstration application in the near-term.

Convergence: Being in the area of nano-materials, this technology could benefit from advances in nano-scale assembly.

Significant Bottlenecks: Bare forests or woven nanotubes (such as those made by Ray Baughman) are very fragile. Also, making good thermal contact to the nanotubes appears to be the greatest challenge in wicking heat away from desired areas. [70]

4.1.15 Psychological Well Being for Humans in Space: Neurofeedback

Application: Neurofeedback for psychological well-being

Problem: Stress, deprivation, isolation, and confinement constitute major risks for the physical and mental health of space explorers during the missions. However, limited resources are available for psychological treatments in space.

Opportunity: The affordability and use of tools such as functional Magnetic Resonance Imaging (fMRI) and electroencephalography (EEG) elucidate the spatial and temporal elements of neuronal activity. The increase in graphical computational power and the improvement in 3D perception devices make the participants immerse more in a Virtual Reality (VR) environment.

Exponential Technologies: Neural Technologies and Medicine and Computing and Networking

Grand Challenges: Staying There, Space Exploration

Other Connected Ideas: Cyberspace Worlds

Estimate of Potential Benefit: Utilizing the real-time noninvasive neural signals recorded, neurofeedback and virtual reality will help the subjects to learn how to control over their own brain activation [50]. Success can be also found in the treatment of attention deficit disorder, pain control and reduction in anxiety, which may occur during long space exploration.

Who is doing it:

(a) Omneuron demonstrated that subjects were able to learn through training sessions to control pain perception and pain control [50]

(b) Biofeedback training has been adopted for over 20 years in training astronauts to resist motion sickness [40].

(c) Institute for Creative Technologies of the University of Southern California uses VR to treat stress in Iraq war veterans [137].

Time Scale: 1 year

Convergence: The synergy found where the creation of new computers, sensors, and communication devices and research relating to new biological and medical technologies converge will extend the use of elaborate new tools to the complex operational environments facing today's and tomorrow's astronauts.

Significant Bottlenecks: Today's fMRI machines offer the highest spatial resolution for the noninvasive study of human brain activity. However, their large size and weight makes both inadequate for measurements in real-world operational environments. Currently, EEG represents the only available portable, brain-imaging equipment suitable for this purpose; yet, it has the drawback of a relatively modest spatial resolution regarding the source localization of measured activity..

4.1.16 Medical Treatments in Space: Transcranial Magnetic Stimulation

Application: Neurological Disease Treatment

Problem: 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. However, limited resources are available for medical treatments in space.

Opportunity: Transcranial Magnetic Stimulation (TMS) is a noninvasive brain stimulation technique which showed promising results in treating a range of neurological diseases [124].

Exponential Technologies: Neural Technology and Computing

Grand Challenges: Staying There.

Other Connected Ideas: Stem Cell Therapy

Estimate of the Potential Benefit: 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 [124]. TMS is promising to provide easier treatments to a variety of neural diseases in space given limited medical resources.

Who is doing it: TMS is already U.S. Food and Drug Administration (FDA)-approved and widely used in depression treatment [124].

Time Scale: 1 year

Convergence: In addition, utilizing the real-time noninvasive neural signals recorded, neurofeedback and virtual reality will help the subjects to learn how to control over their own brain activation [50]. Success can be also found in the treatment of attention deficit disorder, pain control and reduction in anxiety.

Significant Bottlenecks: TMS stimulation spreads and lacks selectivity.

4.1.17 External Propulsion

Application: Launching payload into LEO with external propulsion space launch system

Problem: Today space access is too expensive and unreliable as discuss in Space Access Problem Space discussion.

Opportunity: Make space access affordable for medium- and small-sized businesses; put space on an exponential curve of growth through introduction of exponential technologies into launch system

Exponential Technologies: Material manufacturing and nanotechnology; computing; electronics

Estimate of the Potential Benefit: Development and reduction to practice of external propulsion space launch system can bring the cost of space launch down to below $1000 per kg into LEO. Space launch can become reliable, cheap and convenient.

Timescale: 5-7 years

Challenges: Development of a heat-exchange engine; development of beaming facility that connects energy station on the ground with the launch vehicle; public acceptance of a paradigm shifting technology.

4.2 20-year Time Horizon

4.2.1 Space Based Solar Power

Application: Collect solar energy from space and beam it to Earth.

Problem: Today, with a global power consumption of 12TW [127], we are reaching the end of the energy supplies we have come to use so commonly. It is expected that by year 2020 the global power consumption will be nearly 20TW. It is becoming more expensive and more risky to search for fossil fuels to power our cities, and the effects the combustion of these fuels is having on the environment is becoming awfully damaging. Over 85

Opportunity: The most promising way to harness solar energy to power the entire globe is through a technology called Space Based Solar Power (SBSP). The idea is not new, in fact it was first hypothesized nearly forty years ago. SBSP simply takes advantage of the large amount of solar energy striking the Earth from orbit, which is 1.366 kW/m^2. A SBSP plant will collect gigawatts of energy in orbit, electromagnetically beam it to the Earth at a suggested frequency of 2.45 GHz [36], and then use it in a multitude of forms. A single kilometer wide band of geosynchronous Earth orbit receives enough solar flux annually to equal that of all the energy within all the known oil reserves on Earth today [112].

Estimate of the Potential Benefit: SBSP can provide solar energy to anywhere on Earth 24 hours a day. Every nation on Earth will be taken out of the dark ages once this system becomes viable.

Who is doing it: Space Energy is a commercial company building a prototype SBSP system to be launched to LEO [131]. JAXA also has plans to build a SBSP program.

Current Bottlenecks: There are several advancements that Exponential technologies could deliver that would enable SBSP to be economical, at which point it will unarguably be undertaken. The first obstacle is access to space. If a new form, or at least cheaper form, of space access were to be implemented the materials to build the SBS plant could be taken to space.

Another option however would be to utilize the materials on the moon, asteroids, or space debris to construct the SBS plant. Since the current launch cost is 10,000 dollars per Kg, as soon as materials are brought from anywhere but Earth the cost of the endeavor decreases by nearly 10,000 dollars! In fact, a Lunar Power Beaming Station could be most effective as lunar materials would be used to build the station without having to move the materials off the lunar surface, however the timescale on such a project is far off. This is because with todays technology it would be too costly to build the structures on the moon, transmit the power to GEO satellites, that could then redirect the power to rectennas on Earth. It also seems unlikely that a government space program will focus on this goal in the near term, and it would take a government agency to afford such a project [127].

Another obstacle limiting SBSP is that most plans suggest photovoltaics as the source of capturing solar energy to then be converted to microwave. Photovoltaic (PV) technology is however quite inefficient, with maximum efficiencies on space rated PV cells at around 25

4.2.2 Space Based Stirling Engine

Application: A novel method to harness solar energy on the moon, asteroid, or space using sterling engines

Problem: Are there other ways to harness the power of the sun other than photo voltaic? A method that is more efficient and possibly offers a better means of energy storage?

Opportunity: Stirling engines offer an efficient means of energy production but are limited in use due to the large temperature differential needed, the environment of space however offers the temperature differentials needed to make this form of energy production applicable.

For Stirling engines, the energy can roughly be estimated as $E \approx C_p(T_2 - T_1)$, where E = energy, C_p = pressure coefficient, and $T_2 - T_1$ = temperature differential. Since no combustion takes place within a Sterling engine the energy output is much less compared to the combustion engine for most conditions, however, when the temperature differential is on the order of hundreds of degrees Kelvin we find larger energy outputs.

On the lunar surface the temperature difference between the shaded and unshaded regions is roughly 530 K. A Stirling engine could operate on the lunar surface with the hot side facing the direction of the sun and the cold side being on the underside in the shadow of the device. With the use of energy storage devices a lunar Sterling engine could supply energy to a lunar base while also storing residual energy to be used during the Lunar night. A lunar day/night lasts 14 Earth days.

The same idea can be applied in open space or orbit with a bit of attitude control to keep the hot and cold sides in proper orientation. And with advancements in nanotechnology, such as Buckypapers, the hot and cold side of the device can be constructed to be perfectly absorptive or reflective to maximize temperature extremes.

Estimate of the Potential Benefit: When a lunar base is established it will be very important to harness as much solar energy as possible during the 14 Earth day long Lunar day since the Lunar night is just as long. Storing energy for the lunar night is also important. The sterling engine offers some unique methods to store the extra energy for the lunar night and possibly create more abundance of energy compared to PV's.

4.2.3 3D Printer in Orbit

Application: a 3D Printer in orbit will be able to print antennas, reflectors and solar cells.

Problem: Sending up antennas, reflectors and solar cells to orbit is both expensive, difficult and inefficient. Expensive in proportion to the weight, difficult to build structures that will stand the rigour of launch, and inefficient because the structures are built to support high accelerations and high Gs, while once in orbit all that structural mass is unnecessary.

Opportunity: A 3D Printer in orbit could print lighter antennas, reflectors and solar cells without cumbersome structural restrictions, using minimum materials. The supply materials to the 3D Printer could be either sent from Earth (in high gravity launches); refurbished from existing orbiting spacecraft, antennas and reflectors; or eventually provisioned from asteroid mining.

Exponential Technologies: Nanotechnology, Robotics.

Grand Challenges: Robotic Exploration, Human Exploration, Staying There

Other Connected Ideas: Asteroid Mining; 3D Printing; In-Orbit Refurbishing

Estimate of the Potential Benefit: Lighter and bigger structures in space for communications, energy harvesting and others.

Who is doing it: -

Time Scale: 10-15 years.

Convergence: Robotics, Computing and Networks, Materials, AI.

Significant Bottlenecks: Making a 3D printer work in μgravity, robotic manipulators to extract and assemble 3D-printed parts without humans present

4.2.4 3D Printing in Space

Application: 3D printing space exploration tools and parts on an "as-needed" basis.

Problem: Manufacturing space exploration tools is a long, laborious process. A simple example is in which a basic tool bag can take months to years to build and cost over $100,000 [31].

Opportunities: Some metals, ceramics, and plastics can be printed with current 3D printing technologies here on Earth, and the palette of materials is expanding exponentially. However, the current 3D printing model will not work in microgravity environments. The technologies today use an electron beam in a vacuum chamber to locally melt parts of a layer of metal dust to build up the structure voxel by voxel, layer by layer. Without gravity to form the layer of metal dust, this technique is impossible.

Who is doing it: A new technique called Electron Beam Freeform Fabrication (EBF3) pioneered at NASA Langley overcomes this challenge by extruding a metal directly from a tip [53, 142, 22]. This is a promising technology but needs to improve: the extruding machinery needs to become lighter and its resolution needs to increase. However these are merely problems of engineering that will improve with the exponential increase in the strength of materials.

Enabling technologies: Exponential technologies that will impact 3D printing in space include:

(a) Network and computing systems (leading to faster fabrication).

(b) AI & robotics (automating the process of creating the software on a tool that needs to be created. For example, a 3D scan a machine that is being repaired, and then layout the mock-up of the tool needed to repair the machine).

(c) Nanotechnology (creating a more precise fabrication process and less waste of materials).

Time Scale: The Electron Beam Freeform Fabrication (EBF3) equipment has been successfully tested on the ground [141]. Although the ground equipment is fairly bulky, a scaled down version of EBF3 was created and flown to in near-microgravity on NASA's Reduced Gravity Aircraft [53].

Example 3D Printing Scenario: 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 means 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.

4.2.5 3D Printing Cheap Small Mining Craft

Application: Generating small, cheap, fairly reliable mining spacecraft for obtaining valuable and essential resources from asteroids.

Problem: Current manufacturing processes are expensive and require a great deal of manpower. Therefore, extreme care must be taken to make sure that asteroid mining missions do not fail, which drives the cost up even more. If mining spacecraft could be produced at a fraction of the cost (and a fraction of the size), one mission (one payload) could easily launch 100 or even 1,000 mining spacecraft, each to a different asteroid. This would dramatically increase the chance of success for the mission overall, as well as the fruits of each mission, while simultaneously decreasing the cost of the mission as a whole.

Opportunity: Three-dimensional printing technology has already dramatically cut the costs and time involved in manufacturing products in several industries. As the field advances, 3D printers will be capable of printing with more materials, cheaper, and faster. Shortly, these printers will be capable of simply printing entire mining spacecraft. Effectively, the impact will be equivalent or even better than instantaneously erecting a mass-manufacturing plant for mining spacecraft for $0. As a result, the cost of producing small and effective mining spacecraft will drop sharply.

Exponential Technologies: Nanotechnology, Computing

Grand Challenges: Robotic Exploration, Staying There, Resources

Other Connected Ideas: In order to make this idea work, it will also be necessary to combine the 3D printing technologies with miniaturization, sufficient automation, and robotics.

Estimate of the Potential Benefit: It is estimated that there are trillions of dollars worth of materials available in near-Earth asteroids. Bringing these materials back successfully would not only greatly benefit the mining entity financially, but it would also unlock billions of people on the planet from being restricted by the terrestrial shortage of the materials that are abundant in asteroids.

Who is Doing It:

(a) Professor Hod Lipson at the Cornell Computational Synthesis Library heads the Fab@Home project, which is an open source project that has already resulted in the 3D printing of part of a working robot in 2009[44].

(b) Hod Lipson, along with Jordan B. Pollack, actually succesfully created robots using 3D printing technology as a part of The Golem Project at Brandeis University in the year 2000[118].

(c) Reshko, Mason, and Nourbakhsh have successfully used rapid-protoyping technology to create small robots in the year 2000[122].

(d) Won, DeLaruentis, and Marvodis at Rutgers University are also working on rapidly prototyping robotic systems[152].

Time Scale: We are just now seeing rapid prototyping technology over the last few years that is capable of producing components of mining machines already. We project that within the next 20 years it will be possible to rapidly prototype an entire robotic mining system using 3D printing technology..

Convergence: This opportunity lies at the intersection of advances in 3D printing, design software, materials, microprocessor miniaturization, and robotics.

Significant Bottlenecks: Rapid prototyping and 3D printing is accelerating a fast clip. Since the 3D printing of parts of a spacecraft is already highly feasible, there are no significant bottlenecks that would have to be overcome to achieve this goal.

4.2.6 AI-powered Mining Craft

Application: Mining asteroids cheaply by letting the mining spacecraft handle most, if not all of the decision-making.

Problem: Presently, all space missions require a certain degree of human control. By cutting humans out of the loop, asteroid mining becomes much more viable, not only because it is cheaper, but because thousands of missions can be in operation concurrently.

Opportunity: By leveraging contemporary advances in AI and robotics, it will be possible to create cheaper asteroid mining systems that perform better on their own, without human intervention, than perhaps even human-guided missions would. Since asteroid mining consists primarily of performing mechanical tasks, contemporary AI and robotics greatly advance this field.

Exponential Technologies: Computing, AI & Robotics

Grand Challenges: Robotic Exploration, Staying There, Resources

Other Connected Ideas: This project is connected closely to the project of 3D-printing and rapidly prototyping asteroid mining spacecraft.

Estimate of the Potential Benefit: The ability to launch a swarm of concurrent, cheap asteroid mining missions without human intervention will allow the asteroid mining problem to finally become economically viable.

Who is Doing It:

(a) Countless academic research groups and companies are working on producing better autonomous robotic systems. For a good overview, see Bekey's *Autonomous Robots*, published in 2005, which surveys over 300 contemporary systems[7].

(b) As an example for a future-looking autonomous robotics company, Willow Garage, a company based in Menlo Park, CA, is working on developing a standardized robotic operating system as well as a general-purpose robot that could be eventually applied for usage in asteroid mining. They have just this year given 11 unites to leading research institutions in robotics[67].

Time Scale: There are already many narrowly-intelligent artificial systems, as well as many successful robotic applications here on Earth and in space. It is estimated that in less than a decade, these technologies will be applied commercially to asteroid mining.

Convergence: This opportunity lies at the convergence between Artificial Intelligence and robotics.

Significant Bottlenecks: While there are many significant bottlenecks inherent in designing better AI and better robotics, the AI and robotics systems that are currently present on the Earth in 2010 are more than sufficient to dramatically advance the asteroid mining endeavour.

4.2.7 Asteroid Composition Detection with Microbes and Crystallography

Application: Engineered fluorescent microbes and Crystallography to detect asteroid composition for asteroid mining

Problem: Mining an asteroid entails a huge investment of money, efforts and time. Also, the composition of an asteroid varies much and selecting the right one to mine is a very important step. Heavy metals, some of which very rarely occuring on Earth, i. e. platinum, are heavily represented in certain types of asteroids [93] which should therefore be preferentially picked for mining purposes and the contents brought back to Earth. Importantly, the current periodic table of the elements could be revisited and a new one might be created with all the new elements, if any, that asteroids might carry

Opportunity: Exploit the raw materials from asteroids to address the current shortage of supply of heavy metals on Earth and discover new elements that have not to date reached the Earth's surface that might be represented on the surface of asteroids. A way to detect the composition of the asteroid before docking, is to release engineered microbes that, if in contact with specifically sought for metals/materials, would fluoresce at a particular wavelength corresponding to a specific color. If multiple microbes servicing to detect specific materials were to be released at the same time, then the asteroid would start fluorescing at a combination of wavelengths that could be detected by a Charge-Coupled Device (CCD) camera and resolved in the single components. The intensity of each fluorescence, given the same amount of microbes is released, will indicate the percent composition for each material within the asteroid. Detection of new materials could be addressed by having a Crystallography machine on board that could produce an image of all the crystals (i. e. solid array of atoms) on the asteroid.

Exponential Technologies: Synthetic Biology, Crystallography (X ray, powder diffraction, fiber diffraction, small-angle), Transmission Electron Microscopy (TEM), Communication technology (i. e. space internet)

Grand Challenges: Human Exploration

Other Connected Ideas: The delivery of the microbes and the minining could be done through machines with robotic arms along the same lines of the "Da Vinci" ones developed by Intuitive Surgical, which could be remotely controlled from Earth

Estimate of the Potential Benefit: Filling in on the shortage of resources on Earth and discover new and perhaps useful elements to bring back to Earth for specific purposes, i.e. metallic and materials industry

Who is doing it:

(a) NASA stardust mission

(b) Japan's Hayabusa probe

(c) European Space Agency's comet-chasing Rosetta spacecraft mission

Time Scale: 10 years

Convergence: AI, Robotics, Communication technology

Significant Bottlenecks: Docking the asteroid to start the mining, communication lag from asteroid to Earth if robotic arms were to be remotely controlled, synthetising microbes that have sensitivity for the right metals to be analysed

4.2.8 Lunar Habitat-Building Robot

Application: A lunar-based robot that can build structures with vitrified regolith for lunar-habitat development

Problem: Preparing habitats for human colonies in the moon requires structural materials to be either shipped to the moon or fabricated locally.

Opportunity: Mixing small metallic nano-particles with lunar regolith and applying microwaves to heat and vitrify the mix, or other means of regolith vitrification could be used to produce macro-structures to be integrated into habitat design.

Exponential Technologies: Robotics, Nanotechnology

Grand Challenges: Staying There, Human Exploration, Robotic Exploration

Other Connected Ideas: 3D printing in space

Time Scale: 10–20 years.

Significant Bottlenecks: Technology development

4.2.9 Multi-Surface Robots

Application: New range of various robotic designs that are able to transverse lands or oceans.

Problem: few rovers and robots have been sent for space exploration. Many extrasolar planets may be covered with water, in the future "swimmer robots" would be of extreme use.

Opportunity:

Grand Challenges: Robotic exploration, staying there

Other Connected Ideas: swarm intelligence

Estimate of the Potential Benefit:

Who is doing it: Romela lab (Virginia Tech) is working on new design ideas [114]

Time Scale: 5–15 years.

Convergence:

Significant Bottlenecks: Design

4.2.10 Brain Machine Interface for Robotics

Application: Multitasking at work and communication

Problem: Limited labor in starting up a new colony in space.

Opportunity: Brain machine interface should be utilized to remote control multiple robots and communicate directly with the crew. 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 be able to classify a subset of words in internal speech [135].

Exponential Technologies: Neurotechnology, Biotechnology, Computing

Grand Challenges: Human Exploration, Staying There

Other Connected Ideas: Robotics and Communication

Estimate of the Potential Benefit: Real-time decoding of the resulting neural signals will help us to handle multiple tasks and communicate with multiple colleagues more efficiently.

Time Scale: 10-20 years.

Significant Bottlenecks: Currently, EEG represents the only available portable, non-invasive brain-imaging equipment suitable for this purpose; yet, it has the drawback of a relatively modest spatial resolution regarding the source localization of measured activity.

4.2.11 AI and Synthetic Biology

Problem: Sustaining life on other planets would require establishing basic living conditions, including gravity and radiation protection, providing basic human needs, including breathable air, water and food, and maintaining a clean healthy living environment. This also partially applies to long space trips. Synthetic Biology enables designing new organisms that could help in many of the areas above. However, there is a gap between the DNA codes we can "write," and the real world requirements.

Opportunity: AI could help bridge that gap. Treating DNA as a language, with its syntax, grammar and semantics, AI could enable definition of organism "functionality" in "natural language" - high level description, which is automatically translated all the way to DNA that can be "written" into a new organism. Such an AI driven Synthetic Bio system would take into account all the constraints, at all levels - from gene's, through RNA, DNA, and folding, all the way to the phenotype level.

Exponential Technologies: Synthetic Biology, AI bringing the paradigm shift

Grand Challenges: Staying There, Getting There

Estimate of the Potential Benefit: Synthetic organisms could help producing and recycling air, water and food, as well as facilitate terraforming.

Time scale: Currently we know how to write around 1 million genes, sufficient to modify single cell organisms. As an exponential technology, we expect to be able to design single-cell organisms within 5 to 10 years simple multi-cell organisms within 10 to 15 years.

Convergence: Synthetic Bio could eventually lead to enhanced humans, and human-like bio-robots.

Significant Bottlenecks:

(a) Much of the constraint and mapping space between DNA level and high level functions is not known.

(b) Resistance to artificial life forms and fear of the perils it could involve.

4.2.12 AI driven Synthetic Biology for space exploration

Problem: Space exploration would require a human friendly environment maintained inside a spaceship, or in a small base on another planet, for an extended period of time. This includes provision of clean air, clean water, and food.

Opportunity: Synthetic Biology enables the design and manufacturing of new organisms that would help:

(a) creating and recycling air: synthetic organism/bacteria that use toxic atmosphere to produce oxygen,

(b) purifying sewer water: synthetic organisms that feed on the contaminating materials

(c) producing food: synthetic organisms that process nutrient to produce food in solid or liquid form (such as milk, pills with specific properties)

(d) In the context of space exploration, typically involving only few people, such solutions can be modular and movable, containable small/ confined/ constrained spaces - tanks, rooms, etc...

Exponential Technologies: AI, Synthetic Biology

Grand Challenges: Staying There, Getting There.

Estimate of the Potential Benefit: Consistent, cheap and light supply of human life needs.

Time Scale: Currently we know how to write around 1 million genes, sufficient to modify single cell organisms. As an exponential technology, we expect to be able to design single-cell organisms within 5-10 years simple multi-cell organisms within 10-15 years.

Convergence: Synthetic biology could eventually lead to enhanced humans, and human-like bio-robots.

Significant Bottlenecks:

(a) There is a gap between the DNA codes we can "write" and the real world requirements. AI could help bridge that gap.

(b) Resistance to artificial life forms and fear of the perils it could involve.

4.2.13 AI and Synthetic Biology for Colonizing Other Planets

Problem: Colonizing other planets would require establishing proper large scale living conditions for an increasingly large population, including:

(a) Supply of air, water and food.

(b) Radiation protection

This would require massive change of the environment to suit human existential needs - terraforming.

Opportunity: Synthetically created organisms could help terraforming other planets by including:

(a) Generation of an atmosphere by transforming available materials into air.

(b) Transforming local soil

(c) Synthetic plants designed to grow in the new environment, making a food source.

(d) Generate water from locally available materials.

Exponential Technologies: AI, Biotechnology

Grand Challenges: Staying There, Getting There

Estimate of the Potential Benefit: Providing human life necessities by transforming locally available materials, requiring a load of bits (information) rather than atoms (matter).

Who is doing it:

Time Scale: Currently we know how to write around 1 million genes, sufficient to modify single cell organisms. As an exponential technology, we expect to be able to design single-cell organisms within 5-10 years simple multi-cell organisms within 10-15 years.

Convergence: Synthetic Bio could eventually lead to enhanced humans, and human-like bio-robots.

Significant Bottlenecks:

(a) There is a gap between the DNA codes we can "write" and the real world requirements. AI could help bridge that gap.

(b) Resistance to artificial life forms and fear of the perils it could involve.

4.2.14 Bioreactors for Terraforming

Application: The use of microorganisms genetically modified could improve the life support systems which are necessary in the process of soil terraforming on other planets in order to reach a sustainable production of food, water, oxygen, and waste treatment.

Problem: Last year marked the 40th anniversary of our first steps on the Moon, and within next decades it is hoped that humankind will have established a settlement on Mars. Space is a harsh environment, and technological advancements and operational challenges, such as the management of life-support systems, food, waste disposal, and nutrition due to long-term confinement will be required to ensure that humans survive interplanetary journeys and settlements [81]. Because of this, one main challenge will be to redefine environments that cannot at the moment host life, as we know it, and turn them into habitable ones, so as to ensure the first human colonization into space [72].

Due the life support systems do not permit long staying into space, and the models of terraformation could take 100 years or more, new ideas and options using the exponential technologies are needed in order to improve the process and shorten the time [79].

Opportunity: A tiny fraction of Earth's organisms have been exposed to the harsh conditions of spaceflight. Many specimens that have experienced spaceflight were noticeably changed by the event. Space biology has emerged as a critical component of successful human space exploration, fundamental biology research, and our understanding of the limits of life [54, 78]

Although, there are several analogs of environments and models of possible loop close systems [119], the use of microorganisms genetically modified with specific functions could improve the efficiency and performance of the system [95].

Exponential Technologies: Biotechnology (DNA sequencing, genetic manipulation).

Grand Challenges: Staying There

Other Connected Ideas: Genetic manipulation in plant, mammalian, and human cells for similar systems. Synthetic biology.

Estimate of the Potential Benefit: The possibility of becoming any extreme or harsh environment which is not suitable for human life into a habitable one.

Genetically engineered microorganisms have higher performance and better results in specific functions compared to their corresponding wild strains [134].

Who is doing it:

1. Genetic manipulation of microorganisms:

   (a) Group of Dr. Donald A. Bryant, Principal Investigator and Professor of Biotechnology, Biochemistry and Molecular Biology. Pennsylvania State University. USA. Since 2006, he have carried out pioneering research on the genetic manipulation of four phyla of phototrophic bacteria: Cyanobacteria, Chlorobi (green sulfur bacteria), Chloroflexi (filamentous anoxygenic phototrophs), and the newly discovered Acidobacteria.

   (b) Group of Dr. David Dubnau, Investigator in Public Health Research Institute Center, UMDNJ - New Jersey Medical School. Since 1994, he is working on the mechanisms used for bacteria to take up environmental DNA in macromolecular form in a process known as transforming. He uses genetic engineering in order to improve different functions in bacteria as well.

2. Models of Terraforming and bioreactors:

   (a) European Space Agency and Belgian Nuclear Research Centre (SCK CEN) projects (2010).

   - The BASE (Bacterial Adaptation to Space flight Environment) project aims to characterize the behavior of bacteria under spaceflight conditions including cosmic radiation and microgravity.
   - MELGEN-2 (Melissa Genetic Stability study) is involved in the development of novel methods to detect metabolic/genomic instability, microbial contaminants and horizontal gene transfer in the MELiSSA loop. MELiSSA (Micro-Ecological Life Support System Alternative) is a multidisciplinary project of the European Space Agency ESA. It aims at the development of a bioregenerative life-support system to enable future long duration manned space missions (e.g. to Mars) by reconversion of organic gas, liquid and solid wastes into oxygen, water and food. Proper functioning of the MELiSSA loop will be dependent on the stability and axenicity of each of its compartments.
   - MISSEX (Microbial Gene exchange in the International Space Station) project has as aim to study the micro-organisms that are present in confined space ships or space stations.

   (b) Group of Prof. Jeffrey T. Richards, Dynamac Corporation, University of Florida, Space Life Sciences Laboratory, Kennedy Space Center, Florida. He is working in hypobaric environments and its relationship with microorganisms evaluating the implications for low-pressure in life support systems during human exploration missions and terraforming on Mars [123].

Time Scale: The genetic manipulation is been done in the laboratory for several years [134]. However, the design of bioreactors for life support systems and terraforming, is still theoretical or has different uses on Earth. The real application could be in the near-term (5 years) using the new microorganisms.

Convergence: Robotics to ensure automatic manipulation of life support system bioreactors. Nanoparticles could mimic the bacteria functions. Synthetic biology.

Significant Bottlenecks: Several models of terraforming, principally Mars, using microorganisms assume that the initial stage of planetary engineering has been accomplished, and has a denser atmosphere, in which liquid water is stable, and a higher average surface temperature such as the case of Mars [107]. In addition, the use of microorganisms as a trigger of terraformation present several ethical issues associated with bringing life to other planet center on the possibility of indigenous life and the relative value of a planet with or without a global biosphere [49].

4.3 30-year+ Time Horizon

4.3.1 Nanotech Space Suit

Application: A lightweight, mobile spacesuit of tomorrow

Problem: The spacesuits currently in use weigh hundreds of Earth pounds, take up too much space, and are extremely immobile. The immobility of the space suit and it's large mass is due to the fact that it has to protect the astronaut form the harsh environment of space.

Opportunity: Protecting from radiation is extremely important. Carbon Nanotube membranes could be used to make a very thin material to be worn as a radiation garment, similar to a wetsuit, but not necessarily skin tight.

Estimate of the Potential Benefit: Will allow future space explorers more freedom while doing extra vehicular activities.

4.3.2 Nanoengineered Smart Materials

Application: Smart materials for space habitats and spacecraft with integrated sensors, morphing and self-healing properties.

Problem: Space habitats and spacecraft are structures built in the limit of technical capability, and subject to multiple hazards.

Opportunity: Using nano-scale engineering, smart materials can be developed that include, in the same structure, sensors for structural stability and habitat conditions, and that can adapt rapidly at different conditions. Nanomaterials with the ability to self-heal, morph for different functionalities and respond in real time to threats like radiation, or micrometeorites.

Exponential Technologies: Nanotechnology, AI.

Grand Challenges: Staying There, Human Exploration, Getting There

Other Connected Ideas: Nano-Fabricators

Estimate of the Potential Benefit: Lighter, safer structures for use in space, or getting there.

Who is doing it: -

Time Scale: 15–25 years.

Convergence: Nano, Computing and Networks, AI.

Significant Bottlenecks: Nanoassembly technology.

4.3.3 Cheap Access / Space Elevator / Carbon nanotubes

Application: Cheap Reliable Access To Space

Problem: The cost of space access is too high for major developments to take place

Opportunity: With advancements in carbon nanotubes a geosynchronous satellite can be used as a space elevator, lifting payloads to orbit on a carbon nanotube wire.

Estimate of the Potential Benefit: Opens the space frontier

Bottlenecks: Carbon nanotubes that are kilometers long need to be invented before this technology has any chance of happening.

4.3.4 Brain Machine Interfaces for Remote Sensing/Presence

Application: -

Problem: The problem with today's external Brain-Machine Interfaces (BMIs) is their limited resolution, inability to connect well to the inner parts of the brain, usability problems due to an abundance of sensors to be attached. Neurally connected BMIs afford surgery operations. FMRI and other imaging technologies provide better resolutions, increasingly in real-time fashion.

Opportunity: Portable as well as implanted BMIs with neural resolution can provide a much richer remote sensing experience compared to today's remote presence technologies (HMD, Caves, Immersion technologies, mixed reality). If remote robotics provide rich sensing opportunities from exploration, such experience can be reflected within the BMI in a much better fashion than today.

Exponential Technologies: Nanotechnology, Biotechnology, Neurotechnology, Computing.

Grand Challenges: Robotic Exploration

Other Connected Ideas: Neurobiology, Nano/Materials Science.

Estimate of the Potential Benefit: Full immersion with regards to remote places, wider bandwidth of sensing experience through real-time filters, real-time augmentation of experience.

Who is doing it:

(a) Fraunhofer IGD

(b) MIT MEDIA LAB

(c) Merl

Time Scale: 5 years limited visual/retinal,10 years partial real-time, 30 years full immersion

Convergence: Nanotechnology, Neurotechnology

Significant Bottlenecks: Complete mapping of the brain, lasting sustainable neural/electronic connection. Representation resolution. High bandwidth connection to remote areas in space.

4.3.5 Cheap swarm spacecraft for exploration

Application: Mediated human exploration of space through the extension of our bodies into swarms of robots and spacecraft.

Problem: Exploring the solar system for fun and profit (both for research and prospecting purposes), will be regarded more and more as a fundamental activity in the coming decades. Findings will lead to great riches, and people will invest heavily in this new gold-rush. However, there are limits to human exploration: it is more risky, more expensive, and humans can only be in one place at a time

Opportunity: Building sensory interfaces into our spacecraft and robots that can extend an operator's sensory input to include feedback from a remote swarm of robotic explorers and unmanned spacecraft can potentially extend the reach of our bodies well into the solar system, allowing for a mediated, yet human exploration of space through other means.

Exponential Technologies: Neurotechnology, AI, Biotechnology, Robotics, Networking.

Grand Challenges: Robotic Exploration, Human Exploration, Getting There, Staying There, Using Space Resources.

Other Connected Ideas: Asteroid Mining; Robotic Exploration Swarms;

Who is doing it: -

Time Scale: 30 years–

Convergence: Bits, Neuroscience and Genetics, Robotics and AI

Significant Bottlenecks: Latency-tolerant brain-machine interfaces and networks.

4.3.6 Emotionally intelligent robot/humanoid for astronauts

Application: Developing an Emotionally Intelligent Robot/Humanoid that serves as an astronaut companion to mitigate the effects of prolonged staying in confined spaces.

Problem: It is hard to stay in confined space for an extended amount of time with other people. Although astronauts are required to be socially outgoing persons who are excellent team players, and are cable of adapting to new changing environments, stress induced from such a compact hight risk environment is a probable outcome, and can affect the astronauts' self control and judgment.

Opportunity: New researches in emotional intelligence and how to program the robots to sense physical gestures and facial expressions, perceive emotions, and interact with other human beings lead the way to a new definition of human-robot interaction that has its results in ameliorating difficult

Exponential Technologies: Computer Networks, Narrow AI

Grand Challenges: Getting There

Other Connected Ideas: Artificial General Intelligence, materials, sensors

Estimate of the Potential Benefit: Reduced levels of stress help astronauts in their mission

Who is doing it:

(a) Scientists at UC San Diego's California Institute for Telecommunications and Information Technology (Calit2)-Hanson Robotics of Dallas, Texas

(b) Carnegie Mellon University's Robotics Institute, Human Computer Interaction Institute, and the Entertainment Technology Center.

(c) MIT Media Lab-Personal Robots

Time Scale: 5-10 years

Convergence: Brain, HCI, Nanotechnology, Design

Significant Bottlenecks: Being able to mimic the fine details of facial expressions, universality in emotional expression.

4.3.7 Artificial General Intelligence (AGI) rovers

Application: Applying AGI in exploration rovers to be sent on future mission to planets.

Problem: New environments present different and unexpected challenges; obstacles, atmospheric conditions, geological dangers all constitute a part of the unknown circumstances that the rover might encounter. Making the right decision is crucial to safely navigate and complete a successful mission. Current rovers have no ability to predict or estimate danger, and have no advanced decision making capabilities, thus making them vulnerable to sudden or subtle changes in their surrounding, resulting in endangering their mission and its outcomes.

Opportunity: Advances in reverse engineering the brain and modeling how the mind works, can give us the basis of how to implement a general approach of problem solving mechanism that can be widely used in different situations. If applied and integrated in space exploration robots, it can facilitate its mission, making it more capable at gathering and analyzing information, predicting potential beneficial areas of exploration even if it was not originally planned in its mission.

Grand Challenges: Getting There, Staying There, Robot Exploration

Exponential Technologies: Computing, Networking, AI, Robotics

Estimate of the Potential Benefit: -

Who is doing it:

(a) Numenta Project (Jeff Hawkins)

(b) OpenCog/Novamente (Ben Goertzel)

Time Scale: Significant progress is being made towards a better understanding of how the mind works, better models would probably emerge in the coming few years and according to Ray Kurzweil we will achieve AGI between 2015 and 2045.

Convergence: Brain, HCI, Medical Scanning Instruments, Computation

Significant Bottlenecks: The human brain complexity, information processing, different theories and studies in the scientific community

4.3.8 AI and Synthetic Biology for Space Related Human Enhancement

Problem: Space exploration, including life on other planets, requires providing human life necessities during potentially long space trips and long stays.

Opportunity: One approach would be to provide the necessary living conditions and needs. However, another could be to modify the required living conditions and needs by enhancing human-beings, adjusting human physiology to space conditions, including:

(a) adjusting for micro, or no gravity

(b) resistance to radiation

(c) adjusting for a different atmospheric blend and resistance to currently poisonous materials.

Exponential Technologies: AI, Biotechnology

Grand Challenges: Staying There, Getting There

Estimate of the Potential Benefit: Dramatically reducing the costs and efforts required for space exploration and colonizing while increasing survival chances.

Who is doing it:

Time Scale: Currently we know how to write around 1 million genes, sufficient to modify single cell organisms. As an exponential technology, we expect to be able to modify human DNA in 20 to 30 years.

Convergence: Human enhancement techniques could also help generating human-like robots.

Significant Bottlenecks:

(a) There is a gap between the DNA codes we can "write" and the real world requirements. AI could help bridge that gap.

(b) Resistance to artificial life forms and fear of the perils it

4.3.9 Whole-brain simulation

Application: Whole Brain Simulation

Problem: Lack of knowledge in brain-mind relationship

Opportunity: As the computational power is exponentially increasing, simulation of how the human brain works will become feasible.

Exponential Technologies: Neural Technology and Computing

Grand Challenges: Staying There. Space Exploration. Medicine in Space.

Other Connected Ideas: Artificial General Intelligence

Estimate of the Potential Benefit: Cure neural and psychological diseases. Enhance human performance. Develop AI based on the understanding of brain function.

Who is doing it:

(a) Blue Brain Project, IBM Zurich, Switzerland, attempts to reverse-engineer the mammalian brain, in order to understand brain function and dysfunction through detailed simulations.

(b) DARPA SyNAPSE, IBM Almaden Research Center, USA, investigates innovative approaches that enable revolutionary advances in neuromorphic electronic devices that are scalable to biological levels.

Time Scale: 20 years

Convergence: Artificial intelligence will be further advanced by fully understanding the electrophysiology of human brain.

Significant Bottlenecks: None of the existing invasive and noninvasive neural signal recording techniques offer sufficient spatial and temporal resolutions to study individual neuronal activity during behavior in real-time.

4.3.10 Uploading intelligence

Application: Uploading complete or partial human brains into space robots for exploration.

Problem: Taking humans into deep space is risky, expensive and slow.

Opportunity: To build exploration robots that can receive an "uploaded" human brain for science, exploration and other missions.

Exponential Technologies: Neurotechnology, AI, Biotechnology, Robotics, Networking.

Grand Challenges: Robotic Exploration, Human Exploration, Getting There, Staying There.

Other Connected Ideas: High-throughput exploration through swarms of sentient spacecraft; robotic exploration;

Estimate of the Potential Benefit: -

Who is doing it: The preliminary groundwork is being laid by IBM's Synapse and Blue Brain projects.

Time Scale: 30 years

Convergence: Bits, Neuroscience and Genetics, Robotics and AI

Significant Bottlenecks: Technical—the capacity to scan brains functionally and the capacity to run them on space-rated hardware must be developed.

4.3.11 The Ultimate Fate of Space Exploration: Self-Replicating AGI Systems

Application: Exploring more and more of the far reaches of space without any human assistance.

Problem: Typically today, all space missions require human intervention. This greatly increases the cost and time involved. Additionally, all missions must originate on Earth, which places a fundamental limit on the distance from the Earth that can be explored in any given time. The optimal situation would be exploration missions that do not require human intervention, and which can replicate themselves *while in space*, so that each subsequent generation of missions can explore further and further into deep space.

Opportunity: The ultimate manifestation of Artificial Intelligence is known as Artificial General Intelligence (AGI). AGI systems are characterized by being good at learning and innovating on their own, much like humans do, and can become proficient at a wide array of tasks. This is in stark contrast to currently available narrow AI systems, which are only suitable for specifically engineered tasks. By combining AGI with self-repicating systems, it will be possible to create systems which explore the far reaches of the universe without any human intervention. These systems will replicate themselves in the far reaches of space, without ever having to return to Earth. They will be capable of learning new things about Space, drawing their own conclusions, and making novel decisions, without any human intervention.

Exponential Technologies: Computing, Nanotechnology

Grand Challenges: Robotic Exploration, Staying There

Other Connected Ideas: This project is the logical extension of a more near-term project that involves creating large numbers of semi-autonomous spacecraft that are capable of exploring limited regions of space and reporting back. By taking that project to the next logical extension, those semi-autonomos spacecraft become fully autonomous. Finally, combining this idea with self-replicating technology will allow the project to grow exponentially without human intervention.

Estimate of the Potential Benefit: This project is likely the culmination of space exploration. Self-replicating robotic spacecraft will be able to cover far more reaches of space than humans would ever be able to do, due to their exponentially growing nature. It is estimated that the maximum amount of space will be explored using a technique such as this one.

Who is Doing It:

(a) Newton Howard and Marvin Minsky are leading a project at MIT called the MIT Mind Machine Project that has potential to create an intelligent system powerful enough for this task[18].

(b) Ben Goertzel is leading a non-profit open source project called OpenCog, as well as a commercial AGI research venture called Novamente, both of which have the potential to create an intelligent system powerful enough for this task[29].

(c) Professor Gregory Chirikjian is working on research about self-replicating robotic systems at Johns Hopkins University, and has successfully prototyped several[37].

(d) Chirikjian has worked with Suthakorn and Zhou to explore the idea of self-replicating machines for space exploration as well[136].

Time Scale: In order to embark on a mission such as this one, AGI must be available alongside self-replicating machines. It is estimated that this will not happen until 30+ years in the future.

Convergence: This project lies neatly at the intersection between Artificial Intelligence, computing power, miniaturization, nanotechnology, and self-replication.

Significant Bottlenecks: It is currently unknown how any AGI system would function, or precisely how any self-replicating machine would actually be deployed. Therefore, an extensive amount of research and development would have to be performed before this project could be commenced.

Glossary

3D Printer a device which produces 3D objects from a bulk material, frequently by a process of layer-by-layer deposition. 41

Crystallography experimental science of determining the arrangement of atoms in solids. X-ray crystallography and electron crystallography are used to investigate protein structures in biology.. 33, 44, 45

ideal rocket equation an equation which relates the maximum change of speed of a rocket with the I_{sp} and the initial and final mass of the rocket.

$$\Delta v = I_{sp} g_0 \ln \frac{m_0}{m_1}$$

where m_0 is the initial total mass, including propellant; m_1 is the final total mass, I_{sp} is the specific impulse of the engine, g_0 is the initial acceleration due to gravity, and Δv is the change of speed of the rocket over the entire period. 6

payload fraction the fraction of a launch vehicle's mass on the launchpad which is allocated to the object(s) being launched (payload), rather than structural materials, fuel, etc. 6

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. 6

Vint Cerf father of the internet. 35

Acronyms

AGI Artificial general intelligence: also known as "strong AI," a hypothesized future technology with intelligence, creativity, and general problem-solving capabilities equal to those of a human; see also subsection 3.3. 37, 54, 56

ARPANET Advanced Research Projects Agency Network: an early predecessor to the Internet. 34

BMI Brain-Machine Interface. 52

CAD Computer-Aided Design. 37

CCD Charge-Coupled Device. 45

EEG electroencephalography. 38, 39

FDA U.S. Food and Drug Administration. 39

fMRI functional Magnetic Resonance Imaging: a technology for measuring brain activity which is well-known and widely used, but with low spatial resolution. 38, 39, 52

ISS International Space Station. 10, 12

JPL Jet Propulsion Laboratory. 35, 36

LEO Low Earth Orbit. 35, 40

MFC Microbial Fuel Cells. 31

PV Photovoltaic. 41

Techsat21 Technology Satellite of the 21st Century. 36

TEM Transmission Electron Microscopy. 45

TMS Transcranial Magnetic Stimulation. 39

VR Virtual Reality. 38

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