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Prospectives in Deep Space Infrastructures, Development, and Colonization

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Abstract

The realization of the long studied cost reduction benefits of reusable rockets is expected to revolutionize and enable both commercial deep space beyond Geostationary Earth Orbit (GEO) and solar system human colonization. The projections for a myriad of space commercialization activities beyond the current largely positional Earth utilities and Humans-Mars both safe and affordable may now be realizable. This report considers these putative commercial and colonization-related activities, the emerging technologies, the space functionalities to support and further enable them, and envisions the nature of space developments beyond GEO going forward.

Introduction

Some are suggesting that migration of industry into space is the next major move following the migration to the internet. Deep spacefaring/utilization/commercialization/colonization is now rapidly changing from a situation where what is affordable for humans is not safe long term and what is safe long term is not affordable, to both affordable and safe. This is due to a panoply of advancing/revolutionary technologies that are greatly improving capabilities, reducing costs, and thereby enabling safety (Refs. 1-6). Space commercialization, now GEO and below and approaching a $350B/year global enterprise is projected, as deep space commercialization occurs, to grow into an economic engine in the multi trillion dollar range. A, if not the, major initial enabler for this putative metamorphosis with regard to deep space operations is the development, in real time, by commercial entities, of reusable rockets for space access. This appears to proffer factors of 14 Low Earth Orbit (LEO) access cost reductions. Going forward with robotics/Artificial Intelligence (AI) replacing humans and their associated operating costs, even greater reductions are in the offing (Ref. 7and 8). Far less expensive space access is cited as the first issue to be addressed in the National Space Society Space Development roadmap. The historical cost levels for LEO access have long been the major inhibitor of commercial deep space development writ large and for some activities at GEO and below, the domain of current commercial space.

A second seriously enabling set of commercial deep space technologies is the powerful synergistic combination leading to severe miniaturization, lower cost and enhanced capability of the revolutions in IT, computing, robotics, AI, Nano and now quantum and energetics as well as for human health and bio-based In situ Resource Utilization (ISRU) in space, synthetic biology, etc. (Refs. 9, 10). Historically, the cost of a space mission involving humans has been a factor of 500 or so greater than robotic activities. Going forward, autonomous robotics is expected to operate at near human level (Ref. 11), decreasing, except for human colonization, the costs and requirements of human space presence for operation of deep space commercialization activities.

An example of the prospective benefits of seriously autonomous space robotics and much reduced space access costs is their impacts upon the overall feasibility of space solar power. The original vision for such was huge assemblies erected by humans at unaffordable costs. With the cited advances and cost reductions, space solar power cost projections are now much reduced, but still greater than the ever decreasing costs of terrestrial renewable energy and therefore probably more suited going forward for beaming energy in space and onto bodies.

A second example is the situation with regard to the known resources on Mars, including CO_2, water, minerals, etc. The technologies and cost reductions cited should enable robotic manufacture and checkout on Mars, conditions that are needed by humans prior to them leaving Earth enroute to Mars (ref. 12). Such an approach greatly reduces costs and improves operational safety for human exploration and colonization of Mars. In fact, Mars has sufficient resources to be the general store for much of solar system colonization and deep space commercial activities (Refs. 12-19). The National Space Society states that the target for deep space development should be reusable infrastructures.

The present report will review the nature of prospective deep space commercial activities, then delve into the types of supporting deep space infrastructures, applicable advanced/frontier techs and their impacts, and finally speculate as to the potential synergistic deep space commercial and colonization developments. A major purpose of this report is to consider the nature of frontier technological research that would be efficacious with regard to expedited development of colonization and commercial deep space activities which are safe, affordable, and for commercialization generates closed business cases.

Prospective Commercial Space Activities (Refs. 1-5, 13-21)

A. Major LEO constellations of small satellites for high-speed internet and Earth observation, expanding the number of satellites from the order of 1,000 now to some 10,000 plus by 2025. The associated Earth observation capabilities could enable “staring” anywhere 24/7/365.

B. “Utilities” for beyond GEO to service both public and private customers, including communications, energy/fuel, transportation, maintenance/repair, life support, etc.

C. Mining writ large of the Moon, Mars, and asteroids for anything commercially viable or needed for colonization such as water, minerals, He3, rare Earths, volatiles, “mass,” etc. There are purportedly 850 near-Earth asteroids larger than a kilometer in diameter and many smaller ones at lunar distances from Earth or less.

D. Entertainment including virtual reality (VR), videos, virtual presence (e.g. to enable spending an evening exploring Mars from your living room)

E. Collect anti-protons which become entrained in the Earth’s magnetosphere. Anti-protons are exceedingly expensive and, in terms of energetics produced by their 100% matter-antimatter annihilation, are some nine orders of magnitude greater than chemical options.

F. Asteroid defense including detection, tracking, and diversion of threats deemed capable of causing grievous harm

G. Space solar power for utilization on planets, moons, asteroids, in space, delivered via energy beaming using microwave or lasers (Ref. 22)

H. “Space Beach Combing,” which is the identification, collection, destruction, repurposing, and/or remanufacturing of space debris. Of special interest is boosting ISS, in due course, into a parking orbit and scavenging its parts and by the piece (Ref. 21).

I. Space as a trash dump involves putting “trash” in parking orbits for “safe storage,” including possibly some components of nuclear waste depending upon if it could be certified “launch indestructible.”

J. Space manufacturing in orbit, in-space, on other “bodies” or enroute. This could include initially products that are much improved by production in micro g such as pharmaceuticals, fiber-optics, ball bearings, LEDs, solar panels, organs, hearts, and protein crystals. There are also products that benefit from the near absolute vacuum of space, and the manufacture of fuels and on planet/body or in space human or robotic equipage.

K. Space hospitals if microgravity or other in space conditions prove to be efficacious for specific human ills

L. Space tourism and/or colonization of moon(s), Mars, Titan, poles of Mercury, upper atmosphere of Venus, asteroids, in space, including associated servicing and equipage writ large

M. Quantum technologies and quantum computing, utilizing the “quiet” conditions in space, vacuum, low temperature, etc. to delay de-coherence and stabilize quantum states

N. Enhanced positional Earth utilities including telecom writ large, internet, navigation, weather, imagery/Earth observation, resource monitoring, etc., at lower cost and with larger apertures and greater resolution

O. Space weather forecasting for prediction of potential space condition impacts upon electronics both in space and on bodies including Earth

P. Communications and navigation, other satellite functionalities for Moon, Mars, etc. to replicate or improve as is useful the extant “positional Earth utilities” that constitute most of current commercial space

Prospective Commercial Space and Space and Colonization Related Infrastructures

Historically, some space/spacefaring equipage, notably rockets and entry vehicles, have been primarily a one-time use, disposable product. Portions of the shuttle launch configuration were refurbished, reused, including the orbiters, but those refurbishments were not inexpensive. There are serious efforts now to service, repair satellites, and add fuel, a form of reuse. As noted in the Introduction, reusability is a key, apparently effective per the relatively recent industrial experiences, way to reduce cost, at least for space launch. This section addresses space access and other space faring infrastructures for commercial deep space and colonization. Going forward, most of these various space infrastructures would be increasingly operated and maintained by autonomous robotics for reasons of cost effectiveness.

A. Reusable rockets for space access with increased launch tempo and cost reductions (Refs. 6, 7). Analyses indicate that the upside for reusable rockets is a factor of 14 or greater reduction in launch costs. This capability is now being operationalized and based on success thus far, rapid utilization is projected. This significant space access cost reduction will, going forward, have massive impacts upon all commercial space and colonization, changing what is feasible.

The lowest contributing cost for space access using rockets is the cost of fuel, which is only some .4% to 1% of the current total cost. The other some 99% is the cost of the rocket amortized over many flights via reusability and launch related “operations” of all flavors. A major further overall cost reduction approach going forward is to replace humans with “robotics”/AI writ large for manufacturing and operation.

Other additional cost reductions include printing manufacture technologies especially the potential improvements based on Nano printing materials technologies with greatly improved microstructure to reduce dry weight and increase payload fraction. In actuality, adoption of new technologies has only begun to reduce space access costs, which is the sine qua non for more viable space commercialization/colonization through GEO and into deep space.

B. Refueling depots-The fuel to supply such depots could be sourced from Earth, the Moon, Mars, asteroids, etc., anywhere that provides the fuel at lowest cost. These depots could be located in Earth orbit/Earth environs, anywhere suitable/convenient/required in space or on "bodies." The fuel could be chemical of various flavors including methane, H_2/O_2, nuclear reactor, or nuclear battery "fuel." Where propulsive mass and energy have been and can be separated, such as utilization of solar or beamed energy using the various flavors of nuclear energy including positrons, propulsive mass for propulsion utilizing external energy addition could be supplied. The total refueling depot system architecture includes fuel sourcing, production, transportation, storage, and disbursement.

C. Repair/servicing/maintenance functionalities-could be either itinerant or fixed, probably both, could be connected with fuel depots in some cases, and ultimately capable, possibly via printing, etc., of repair/maintenance of nearly everything. Reusability implies possible refurbishment, repair, maintenance, which are not major operational issues with a one-time use approach

D. To service humans, a combination lifeboat, hotel, search and rescue functionality, which could also be sited at fuel depots, utilized for survivability, transit, and space tourism

E. Energy beamers-nuclear or solar powered, including by positrons, the cheap anti-matter. These could be located on bodies, in orbit or in space, and provide an alternative energy/powering source, perhaps involving less cost than producing, handling fuel per se. This would still require propulsive mass for utilization of beamed energy for propulsion vice the many other uses of beamed energy including asteroid defense, mass drivers, on body/spacecraft power and energy, space manufacturing, other industrial/commercial activities

F. Momentum tethers, space elevators, utilized as alternatives for rocket transportation, some have envisaged these as Earth/Moon transport or for even longer distances and they are rather major putative reusable infrastructures, capital projects (Ref. 23)

G. Propulsive Ground Assist-propulsive infrastructures for space access including the slingatron, blast wave accelerators and mass drivers-alternatives to rockets or tethers or as a partial launch assist

H. Space debris cleanup and reuse functionality-simplistically this must be affordable and constitutes a needed public functionality/utility for all of spacefaring. A basic concept is a space vehicle employing an E-M tether powered by either solar or the new NASA NTAC nuclear battery (up to 22 KWs per kg of isotope) which fuellessly collects space debris and deposits it in a space junk yard to be remanufactured or repurposed. This functionality could be part of an in space manufacturing depot (Ref. 21).

I. Space manufacture facilities writ large and space “Business Parks”- located in space, and/or on bodies, all types of bodies, depending upon the business to be conducted, resource availability, transportation costs and products produced

J. Utilities for space colonization including sourcing, transfer, storage, disbursement of food, water, energy, “supplies” writ large, including from ISRU activities

K. Space tugs, in-space transfer, including cyclers, to move raw materials and products. In the absence of time criticality these could employ sails-solar sails, laser sails, magnetic sails, or particulate sails, AKA “sloboats”

L. On body transportation, nuclear/NTAC powered or “fueled” otherwise, for “freight” and humans. Due to the typically rough terrain of bodies, in space flying is probably the most efficacious transportation approach for other than very localized transportation.

M. On body infrastructures-habs, mines, manufacturing plants, energy sources, life support, etc. especially for colonization

Engineering For Reusability

Perhaps the most obvious difference between the design of one time use products and reusable ones is the increased service life duration and cycling therein (Ref. 24). This gives rise to greater durability and damage tolerance considerations. Also, the increased service life necessitates that the product design enables detailed inspection, and to the extent possible, ease of repair with an overall eye to minimizing refurbishment requirements. Experience indicates that reusability should be designed in initially and throughout up to the systems of systems level. Design information required for safety and reliability includes the operational parameters and conditions for all envisaged missions. For reusable rockets, provisions for deceleration and landing are necessary, as these usually reduce the allowable payload weight. Also, the extended operational service requires augmentation of the appropriate testing regime.

Advanced/Revolutionary Technologies For Commercial and Colonization Deep Space Infrastructures

(Refs. 1, 6, 12, 20, 25-27)

A. Miniaturization writ large-nearly everything except humans and the equipage that scales with their size has, thanks largely to the IT and other tech revolutions, long been reducing in size and mass. This is a process that is still ongoing. New technologies are reducing satellites that in some cases were the size of school buses, to much smaller payloads. Also, this miniaturization has enabled cooperative constellations that are more survivable and, in some cases, collectively have greater resolution/aperture. The usual metric of dollars per pound to orbit is being replaced by value per pound.

B. Energetics for in-space, on-planet, and in-orbit propulsion including down sized reactors such as kilo power, orders of magnitude more energy dense nuclear batteries, such as NTAC, and positrons that can now be stored, (nine orders of magnitude times chemical energy density), energy power beaming, magnesium/CO_2 rockets for Mars (there is considerable magnesium on Mars), solar photovoltaic (PV) with increased efficiency, space-based solar power (SBSP), chemical fuels made in space from various resources and structural battery energy storage (multifunctional structures)

C. Electric propulsion-high thrust magnetohydrodynamic (MHD) such as Variable Specific Impulse Magnetoplasma Rocket (VASIMR) and field reversed configuration (FRC) propulsion. Also, electric are mass drivers, Electro-Magnetic (E-M) tethers, the slingatron, solar electric propulsion (SEP), and Hall Thrusters

D. AI/Autonomous Robotics/Sensors – The progress with respect to these synergistic arenas and what they will be able to accomplish is nothing short of astounding. Recent work indicates robots know far more than humans and when overall compared to humans, they are usually far less expensive, exclude operational human error, have more functionalities, far longer duty cycle, and are faster, more efficient, durable, and patient. They also preclude the expensive and weighty equipage required to keep humans healthy. They are not affected the way humans are by radiation and microgravity.

For cost and schedule reasons, space has nearly always been explored robotically. The nominal cost differential between robotic vs. humans is greater than two orders of magnitude. Capability improvements for AI/Robotics are on an exponential growth curve. At a minimum, they could perform the initial preparation for human arrival either in space or on-body, and can (via ISRU) produce most of the equipage required for themselves and humans given the extant requisite resources such as are available on Mars. In addition, the Nano tech revolution is increasingly improving robotic mechanization/capabilities. As the preponderance of safety/reliability issues are due to human factors and given the benefits of autonomous systems, they will probably be safer, more reliable.

E. Materials/printing manufacture – Printing is becoming the most efficacious in-space manufacturing approach. Also, recent printing at the Nano scale is producing materials with much improved microstructures, reduced dislocations and grain boundary issues, with up to a projected 10x potential. Nanotube composites are being worked with an upside of 11x impact in materials. These materials could possibly greatly reduce payload weight and rocket dry weight and increase payload fraction going forward, further reducing space access costs perhaps by another factor of two to three or more.

F. Synthetic biology for producing food (“plants for planets”), materials, electronics, biocement, biopolymers, bioadhesives, life support, biofuels, biomining, bio ore extraction, pharma, biophotovoltaics

G. Inflatables including rigidization, imbedded sensors, actuators, and AI for localized shape changing. Applications include antennas, sails, heat exchangers, solar PV, filtration, mirrors, light buckets, solar concentrators, structures/habs, telescopes, cushions, radiators, sun shades. Inflatables could reduce weight and increase functionalities, and capabilities.

H. Radiation Protection - There are basically three approaches to radiation mitigation, which can be employed combinatorically. Spend less time in space, shield or deflect the incident radiation and biological/medical counter measures to mitigate the resultant health impacts (MCM). In general, shielding requires low Z materials to minimize secondary radiation. Protection approaches include magnetics, fast transits, biological countermeasures (BCMs), three plus meters of regolith or ice igloos and silicon crystals to divert the GCR away from the humans and possibly provide protection while in space suits, albeit the latter may require an exoskeleton to carry the weight/handle the inertia, etc. (Ref. 28).

Overall, due to systems level and conceptual/technological breakthroughs including inexpensive space access via reusable rockets, a low Kw/Kg (Alpha) many MW class nuclear battery, high energy particle reflection from silicon crystals and the syn bio/gene editing revolution as applied to biological/medical countermeasures, the outlook for GCR radiation mitigation has altered over these last years from problematical/unaffordable to a number of potentially viable solution spaces across the TRL spectrum.

In decreasing order of TRL:

- For on moon, planet etc., ~ three meters of regolith
- For in space:
  1. Fast transits (200 day round trips to Mars) via inexpensive Chemical Fuel
  2. Three meter reusable polyethylene “overcoat” via inexpensive chemical fuel
  3. Biological/medical countermeasures, a partial solution in space thus far, TBD going forward
  4. Fast transits (200 day Mars round trip) via 6,000 sec. Isp VASIMR high thrust MHD propulsion powered by an alpha of order one nuclear battery
  5. Magnetic redirection of GCR particles via superconductive (S- C) magnets located extended distances from the spacecraft
  6. Silicon crystal reflection of GCR particles plus shielding for Gamma secondaries. This approach may be applicable to space suits in that event an exoskeleton may be required to handle the additional inertial loads.

Plus significant enabling “tool” developments (codes, in space mouse model lab)

All of these approaches require serious research and optimization with subsequent triage and development to determine the most efficacious for development/utilization. The current unsatisfactory status of GCR radiation mitigation makes such investment necessary due to GCR radiation being the agreed upon most serious human health deep space exploration/colonization issue. Depending upon crew tasking, that could include human Moon operations as well as humans-Mars and in-space humans.

I. Optical and quantum communication-there is increasing utilization of free space optical communications for greatly increased band width. Quantum vector/scaler potential communication is patented but nascent, and purportedly is applicable to planetary distances at high band width.

J. Powered Entry Descent and Landing (EDL) for Mars-The current State of the Art (SOA) for EDL is inflatable heat shields to increase drag area. Employing reusable rockets enabling inexpensive space access, or Variable Specific Impulse Magnetoplasma Rocket (VASIMR), 6,000 seconds of specific impulse (Isp), missions could perhaps afford direct propulsive deceleration such as is used on planets, bodies without atmospheres.

K. Humans are becoming cyborgs including artificial retinas, hearts, limbs, organs, and brain chips and increasingly utilizing direct brain to machine communications, enabling perhaps reduced human health maintenance costs and associated weight and improved human performance.

L. Increasing knowledge of in space and on body resources including water, minerals, underground lakes, lava tubes, atmospheric composition, etc. This is required for development of closed business plans and ISRU for colonization.

M. Tele-everything including tele-medicine, robotic surgery, tele manufacturing, and tele-socialization holographic crew members for psychological support

N. Safety and reliability engineering including fault tolerant or fail safe-safe designs, redundancy, dual use, digital twin, integrated vehicle health management (IVHM), self-repair, larger design margins, assessment/control of cascading failures, etc. Safety/reliability improvements are enabling for most human in-space/on body activities/presence. Nominally, rockets fail at a rate of 1% or greater, this would probably have to be reduced by very sizable factors to enable the commercial airline safety record per takeoff (Ref. 29).

O. In space assembly and repair/replacement – allows assembly of large systems placed by multiple launches. This also includes use of piece parts manufactured in space. Enables larger aperture size and in space repairs and upgrades. Component technologies include sensors, energetics, robotics, AI, and possibly going forward, magnetics and electrostatics. Also, conceivable-to-under study is in space printing of membrane/inflatable/rigidizable materials including biomimetic (e.g. bird trabecular bone like) internal support structures.

P. Artificial gravity for crew quarters for Spaceflight Associated Neuro-ocular Syndrome (SANS), other non-mitigated effects of low to micro g (Ref. 28)

Q. ISRU writ large via the panoply of on body resources, and AI, robotics, energetics, sensors, and printing. Ultimately, Earth independence, especially for Mars (Refs. 1, 12, 18, 30).

R. Fast transits (e.g. Mars round trips in 200 days) “solves” radiation, micro g, psychological issues, and EDL (by going powered). Achievable via either brute force chemical fuels enabled by inexpensive reusable chemical space access or high thrust MHD/6,000 sec. of Isp propulsion (VASIMR), powered by Alpha~1 NTAC nuclear battery (Ref. 28)

S. Sensors writ large, including Nano, quantum sensors for safety, reliability, functionality, navigation, including possibly SBER, structural bond energy release (mechanochemistry, Ref. 31) to detect material flaws

T. Protection from non-thermal E-M health effects (Refs. 32-34). Humans in spacecraft, on other bodies are no longer exposed to the Earth background non-thermal radiation. Instead, along with (mitigated) GCR, other ionizing radiation they are subjected to non-thermal radiation from internal electronics, etc. Some 4,000 studies over more than five decades indicate, especially if pulsed, such low level, microwatts/cm2, nonthermal E-M can have appreciable neurological effects due to alteration of voltage gated calcium channels, and opening the brain-blood barrier among other physiological impacts. Health effects include both central nervous system (CNS) and cardiovascular (CV). Therefore it is probably useful to determine the hab/spacecraft interior non thermal E-M environment and faraday cage if necessary to minimize that portion which is problematic.

ISRU Projections

There are massive resources on Mars obtainable from the atmosphere and extractable from the regolith, which are capable of supporting human colonization on and beyond Mars. Using these resources, existing ISRU technologies could supply water, oxygen, nitrogen, fuels, and building materials on Mars to increasingly reduce the dependence on Earth during the buildup of a colony on Mars. As technologies in the areas of additive manufacturing, energetics and AI/robotics are developed, habitat, and mobility systems, fuel, life support, and building materials become available in quantities capable of building and supporting colonies on Mars and crew return to Earth, missions to go elsewhere in the solar system and fostering space tourism in the inner solar system. Starting with the pre-deployment of robotic ISRU and habitat systems to prepare Mars for the arrival of the first crew, each successful mission within the pioneering campaign yields greater confidence in this ISRU approach, enables functionality checkouts at on planet conditions and sustainable colonization that is both safe and affordable. Then, and only then, will colonization of Mars realize its Earth independence.

Suggested ISRU related research areas include:

1. For Energy: NTAC nuclear battery, micro-fission reactors, radiation-hardened, manufactured on Mars PV and energy storage approaches

2. Habitat: lightweight inflatable habitat with molded-in air locks and "furniture," capable of being buried under some 3 plus meters of regolith.

3. Resource extraction and storage approaches and equipage fabrication from Mars plastics

4. Exploration of "underground Mars" for ice/water, Lava tubes/caves, especially ice caves, geothermal energy, concentrated mineral ores

5. Food production on Mars, including what to do about the perchlorates in the soil which adversely affect the thyroid

6. Autonomous robotics, close as possible to human level operation

7. Fabrication approaches at 0.38g conditions

8. Mars truck design/optimization for transport to/from Low Mars Orbit (LMO)

9. Solution spaces for corrosiveness of Mars dust at the interior habitat conditions of pressure, oxygen, moisture, and temperature

What is particularly interesting is that the C, H_2, and O_2 from the atmospheric CO_2 and the readily available water on Mars would enable the use of plastics to fabricate nearly everything needed by humans on Mars, minimizing the need to mine, process, and fabricate minerals from the regolith.

Putative Futures of Commercial Deep space

The basic enabler of commercial deep space and colonization that is both safe and affordable is reusable rockets, a major start to seriously reducing costs of space access. Most of the new GEO and below activities including space manufacturing as well as commercial activities beyond GEO and colonization have been hostage to the high costs of space access. The cost benefit estimates of rocket reusability with minimal refurbishment are up to a factor of 14, with even greater cost reductions expected to accrue from such as the Nano printed improved materials via improved microstructure and other material improvements yielding reduced payload weights and greater payload fractions from reduced dry weight. Then there is the further major diminution of space access and other costs across the board including for operations expected from switching from direct human labor to robotics, AI, etc. We do not yet know how low the space access costs can go. The fuel cost currently is less than a percent of the total LEO access costs, so there is much room for further reductions. Then there is the increasing miniaturization of nearly everything except the humans, and their equipage that scales with their size. So lighter payloads, especially as autonomous robotics develops, lofted on far less expensive rockets. All of this drives much greater launch demand/frequencies that both reduces costs further and enables increased markets, a virtuous cycle. Many in space commercial activities hitherto not fiscally feasible will going forward probably flourish including space manufacturing and perhaps, given solutions to the in space human health issues, space tourism.

Cheaper space access and energetics developments enable much improved human health and safety including solutions for radiation such as silicon crystals to redirect, three plus meters of polyethylene in a reusable overcoat configuration to protect or fast transits from the NTAC/VASIMR combination, or “brute force” via cheap chemical fuels for fast transits (Ref. 28, 29). Also, enabled by inexpensive space access is artificial gravity and powered EDL, all greatly improving the safety/health concerns associated with mechanical, radiation, and micro g issues. Then there are the developing biological counter measures essentially, by various bio means, moving toward space hardening humans.

As a result, the prime enabling metrics for commercial deep space and colonization, cost and safety, are much improved and the development of a viable commercial deep space industry and colonization should occur. Added to this is the greater knowledge of the on body/planet resources and the AI/robotic/energetics technologies to enable serious ISRU, vice hauling stuff from Earth, and solution spaces for space debris to further improve safety.

As these capabilities and technologies mature and become available, the putative closed business cases for commercial deep space change favorably. Also, inexpensive space access means that it is usually cheaper to bring stuff up from Earth than do ISRU elsewhere, process it and haul it to Earth’s orbit.

The potential closed business cases for commercial deep space include:
(Refs. 1, 20, 21, 35, 36)

1. Commercial space utilities beyond GEO including communications, energy/fuel/transportation, maintenance/repair, life support, etc. These in various forms and flavors will be needed for both government and commercial deep space activities, and especially for colonization. Development has already begun for several of these including communication.

2. Space mining-Asteroid water is particularly interesting, especially if the quantity of Moon water proves to be significantly less and/or extraction costs prove significantly more than anticipated. Given the extant competitive ocean (accessed via the increasingly low cost of renewable terrestrial energy)/other Earth resources, space mining may be more applicable to deep space utilization(s) than for use on Earth.

3. Space beach combing/cleaning up space debris-Given the current situation with respect to space debris and the plans to loft far more satellites, factors more, we will probably be going forward have to move on from avoidance to removal. The legal issues and costs have held that in abeyance. The costs could be addressed via use of E-M tethers powered by NTAC or solar, fuel-less transportation to collect space debris for space manufacture repurposing/remanufacturing (Ref. 21).

4. Space manufacturing–With the space access cost reduction in the offing from reusable rockets the major impediments to space manufacturing, cost and schedule, are greatly mitigated. This capability would also enable in-space manufacture of equipage not suitable for launch, such as too large or too fragile, even in piece parts. Also, there are many products that are either enabled or much improved by in space micro g and/or deep vacuum conditions.

5. Space tourism–When the human health/safety issues (Ref. 28) including safety, reliability, radiation, microgravity are addressed, which are major mission design issues, the inexpensive space access enabled by reusable rockets, etc. should greatly accelerate space tourism.

6. Quantum computing/technologies in space–This is a “new-bee,” with viability and realism yet to be determined. However, for delaying decoherence, maintaining quantum conditions, the temperature, vacuum, and “quiet” conditions of space appear to be of interest, initial experiments are in progress.

7. Space solar power–especially for other bodies and in space utilization initially and possibly, eventually Earth use, depending upon the business case vis-à-vis the ever reducing cost of terrestrial renewables/storage with their massive potential capacity

8. Earth positional utilities–This is the current, very successful, commercial space. Inexpensive space access will make it even more so and several additional areas/functionalities will be enabled.

“Colonization” of bodies such as Mars, a wholly new economy, could, with all the resources on Mars, be essentially self-contained. Mars could, with its resources, become the department and building supply store for the solar system as human colonization moves beyond Mars.

Prospective Commercial Deep Space Architectures, Initial to “Built Out”

It is both interesting and perhaps useful to consider first how the combination of commercial space and space colonization may develop in a synergistic manner (Ref. 37). While many of the commercial deep space business areas, such as space debris cleanup, manufacturing, quantum technology, and tourism, will, certainly initially, be Earth centric with regards to a customer base, these and others including the evolving arena of ISRU/mining and possibly space solar power, would be impacted in a major way by off world colonization, both by robots and humans.

The initial major rational for deep space colonization is purportedly to hedge the bets of the human species from an asteroid impact, a really nasty pathogen, or possibly a major solar storm given the zeroth order dependence of current society on electrons/electronics/electricity writ large. The estimated mortality due to a (analogous to a solar storm) Nuclear EMP attack per the congressional EMP study commission, is seriously major. Mars, given its extensive resources including huge amounts of water, CO_2, minerals, etc. is the obvious first body for colonization. There is considerable interest in the private sector in fostering such colonization.

Initially, robots/AI/printing/solar or nuclear energetics could be used to cool a surface, liquify/extract CO_2 and regolith could be microwaved to extract water. That provides C, H, and O which could then be used for life support via plastics producing nearly all equipage and chemical fuels needed. Given this ISRU derived on site equipage, habs could be constructed and humans sent. They could obviously also be sent much sooner. Going forward, such colonization should be viable and would utilize products, resources from other bodies, and perhaps in space such as space solar power.

With respect to what Earth might need from deep space activities such as ISRU, this is a matter of both if and when. Consider first the vast thus far untapped Earth resources. We can, and going forward probably will, shift agriculture from fresh water plants to halophyte/salt water land plants, which are capable of producing similar products writ large. These grow on deserts and wastelands using saline/salt water. On Earth, some 44% of the land is desert or wastelands, and some 97% of the water is saline. Ocean water contains some 80% of what plants need to grow and there are now ways for plants to utilize nitrogen from the atmosphere. Shifting to saline agriculture using ultra cheap land and water (deserts/wastelands, saline/seawater) would greatly increase “arable” land, release the 70% of the fresh water now used for agriculture back to direct human use, and produce food, fodder, and biomass. This essentially solves, with massive capacity, land, water, food, energy, and climate for many centuries. The ever reducing costs of renewable energy will enable resource and mineral extraction from the ocean, again, with centuries of capacity. The costs and business case for the above and other potential Earth resources then need to be compared to transporting space ISRU products, after extraction, etc. to Earth. This comparison is TBD.

Speculations regarding the farther term frontiers of commercial deep space include space-hardened humans via BCMs, etc., with an end state of the Moravec uploaded “Mind Children,” and terraforming of such as Mars and possibly Titan and Venus. The technologies are developing to move out beyond Mars into the asteroid belt and further in the solar system. However, interstellar apparently requires that we sort out what is really happening at cosmological scales. There are currently serious unknowns or issues with the standard model of cosmology. We cannot find dark matter, dark energy, a huge percentage of what is supposed to be out there, and quantum theory (super accurate for most solar system applications) is off by over 100 orders of magnitude with regard to the cosmological constant. Also, we know not the physics of quantum entanglement, measured recently at greater than some 10,000 times the speed of light. If we ever sort out what is really going on at cosmological scales we may be able to do reasonable interstellar travel, and then we will become a cosmic, and not just a solar system, civilization.

What is needed in the nearer term over the next few decades for development of commercial deep space and space colonization:

- Solutions to space debris, such as the one described herein
- Solutions to the many space related human health issues, the foremost of which is radiation protection, solutions for radiation protection cited herein
- Inexpensive space access, reusable rockets to start, early days yet
- Reliability and safety improvements (Ref. 29)
- In space/on body resources mapped, a work in progress

- Advanced power and energy options researched, developed, demonstrated, including fission and positrons
- Closed commercial deep space business plans now possible due to inexpensive space access
- Legalities solved with regard to both space debris and on body resources, becoming ever more critical as deep space mining becomes real
- Trusted AI developed, to reduce costs of deep space development
- Reusability writ large, a major enabler
- Moon/Mars dust “control,” a potential serious health and operability issue
- Optimization of ISRU writ large, including via AI/ Robotics

This would enable going forward:

- Colonization of Moon, Mars, etc.
- Multi-trillion dollar commercial deep space industrial development

It is interesting to speculate as to the potential evolution of humans in space. The combination of developing cyborg capabilities/technologies resulting in less wet electro-chemistry and the reduced gravity and radiation exposures in space will result in changes/evolution of human physiology. Studies on ISS indicate the potential directions of those evolutions in the initial stages. We are studying extremophiles, life forms found in deep ocean vents, Yellowstone pools, ultra-dry deserts and observing the physiological adaptations to space on ISS. These studies provide clues as to what directions human evolution in space might take. Such space and other adaptations could possibly result in some “interesting” alterations, perhaps even sub specie developments (Homeomarsicus?). Moravec (Ref. 38) suggests in the longer term we will explore space as our “Mind Children,” i.e. the uploaded cyborg evolutionary trends will prevail. Ref. 39 is recommended as a source of revolutionary approaches, concepts to achieve cost reductions, and capability improvements for utilizations and commercial development of space.

Concluding Remarks

The costs of space access are falling much due to reusable rockets, and could, with AI/Robotics cutting the manufacturing/operations human labor costs and continued payload miniaturization, reduce much more going forward. Reduced space access costs are the basic enabler for closed business cases with regard to commercial deep space and a catalyst for space colonization.

Power and energy are other enablers of commercial deep space. There are a plethora of frontier energetics approaches requiring R&D/optimization including positrons/storage thereof/utilization, the NTAC very high energy production nuclear battery, Nano PV efficiency into the 70% range, small fission reactors, and ISRU chemical fuels.

Reusable infrastructures of all varieties will be ubiquitous primarily for cost and schedule benefits. NASA has indicated that the Moon developments will be, writ large, reusables.

Considering the effects of inexpensive space access and the massive nearly untapped Earth resources (including deserts, wastelands, saline/salt water, ocean minerals, and the huge capacity of renewable energy), resources acquired in space from ISRU, etc. will probably be used in space, except for space manufactured products used on Earth.

Additional frontier critical technologies include radiation protection including crystals for redirection, size/weight reduction technologies, AI/robotics, printing and syn bio.

Martian colonization has in a few years moved from extremely difficult with regard to radiation, cost, and safety, to increasingly feasible. There are now several ways forward to an affordable and safe humans-Mars mission as a result of reusable rockets, serious ISRU, energetics/fast transits, achievable radiation protection, AI/robotics/printing, and ever greater knowledge of Martian resources, along with a solution for space debris.

Safety and reliability for reusable space systems writ large is very much a work in progress. What could/should change the prospects for commercial deep space going forward and sooner rather than later includes:

- Reusable rockets/inexpensive space access
- NTAC nuclear battery, low weight power and energy
- Autonomy, printing, sensors, computing, AI, ISRU writ large, radiation protection, miniaturization
- Virtual reality, holograms for psychological support
- Mitigation approaches for the many space impacts upon human health

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14. ABSTRACT

The realization of the long studied cost reduction benefits of reusable rockets is expected to revolutionize and enable both commercial deep space beyond Geostationary Earth Orbit (GEO) and solar system human colonization. The projections for a myriad of space commercialization activities beyond the current largely positional Earth utilities and Humans-Mars both safe and affordable may now be realizable. This report considers these putative commercial and colonization-related activities, the emerging technologies, the space functionalities to support and further enable them, and envisions the nature of space developments beyond GEO going forward.

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