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A Compendium of Technological Solution Spaces for Barrier Issues in Aerospace

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Introduction

Over the 1900s and into the 2000s, both aeronautics and from the mid 20^{th} century, space faring successfully developed new technological capabilities that favorably altered nearly every aspect of human society. Air transport largely replaced rail and ship passenger traffic and greatly reduced travel time. Positional Earth utilities in space including telcom writ large greatly aided the buildout of the transformational IT revolution. Both aero and space transformed national security [Refs. 1 – 6]. Going forward, the outlook in civilian aeronautics includes artificial intelligence (AI), emissionless transport aircraft for climate, and a new capability in small electric vertical takeoff and landing (VTOL) aircraft for both service and personal air vehicles. After a century of development, projections indicate personal air vehicles (PAVs) will be deployed as autonomous, safe, quiet, and affordable replacements for automobiles. The societal impacts of the latter are potentially massive, including a new aero market estimated at over $2T. PAVs also provide the ability to live anywhere such as off roads, provide huge societal savings and reduce countryside impacts with regards to roads, bridges, and other auto infrastructures along with increasingly replacing scheduled domestic airline service. Personal air vehicles are a literal major revolution in personal mobility [Refs. 7 – 10]. The recent and ongoing reductions in the cost of space access are slated to enable development of commercial deep space, beyond geostationary orbit (GEO) to the Moon, Mars, etc. There are technological developments underway that could enable humans to become a two-planet society via colonization of Mars, with the development of a viable Martian economy [Refs. 11 – 16]. These envisaged developments in aeronautics and space will require ideation, research, and maturation of viable solution spaces for several barrier issues. For aeronautics, these issues include an autonomous air traffic management (ATM) system for the projected tens of millions of flying things vice the current tens of thousands, advanced batteries including lithium-air at seven times that of lithium ion, and advanced aerodynamics to double transport lift-to-drag ratio for emissionless flight. For space, affordable approaches are needed to clean up the increasingly severe problem of space debris and provide galactic cosmic radiation (GCR) protection for humans, along with serious cost reductions for humans to Mars. For climate, there is a need to determine the detailed physics, chemistry, etc. of cloud micro physics. Aerosols are equal in magnitude and opposite in sign to carbon dioxide (CO_2) regarding effects on climate. Because aerosols involve extremely complex processes, they require far more detailed study for improved climate projections. In addition to these barrier issues for space and aeronautics, there are several serious barrier issues common to both. They include cost, energetics, safety, artificial intelligence (AI)/autonomy, the developing AI/robotic technological competition regarding onsite human aeronautics and space, and tele-everything, immersive presence, the virtual age, etc. The present report examines these barrier issues, their putative solution spaces, and their potential major combinational societal impacts – altering/expanding both aeronautics and spacefaring and enabling large new markets, lowering costs, improving human health and safety, and altering societal lifestyles.

Barrier Issues Common to Both Aeronautics and Space

Both aeronautics and space faring have the common issues/requirements of affordability/cost reduction, light weight, available power/energy to perform the mission(s), and safety and health for onsite humans, along with going forward autonomous robotics capability improvements for both cost reduction and capability improvements. In addition, both aeronautics and space are beset by the rapid development of superb virtual, immersive presence as a lower cost and effective alternative to such as physical travel and presence. The dominant system metrics in aerospace are mission capability, cost, and safety. Energetics and AI can reduce cost and increase capability and safety.

Cost - Aerospace is currently a buyer's market, where competitiveness depends upon cost reduction(s) and delivery cycle [Ref. 17]. There are two fundamental approaches to cost reduction: conventional and unconventional. The conventional approach is often incremental, evolutionary, and involves examining all aspects of supply, production, and operation in a process usually termed "continuous improvement". The unconventional approach involves ideating, innovating solution spaces with often greater-to-far-greater performance and functionality at the same or lower cost. Typically, the unconventional approach, which requires embracing risk and courage, yields far greater effective cost reduction and often creation of wholly new markets. Analyses of major determiners of costs, both regarding production and product, indicates that 80% to 90% of the cost is "designed in" at the initial 10% conceptual and design stage [Refs. 18, 19]. This necessitates serious early efforts involving a multiplicity of concepts and ideas that are triaged for the major, real-world metrics, one of the most important of which is cost. That in turn requires superb knowledgeability regarding worldwide technology, marketability, real-world metrics, societal requirements-to-desirements and competitiveness, along with raw ideation and inventiveness. Increasingly over decades and as the machines have improved, aerospace research has shifted from expensive experimentation to less expensive computations, providing faster response and increasingly examination and optimization of putative approaches. AI is developing the capability to ideate and optimize designs and is expected to reduce cost and be more efficient and effective. The information technology (IT) revolution has enabled major cost and size reductions and capability increases for avionics.

Major aeronautical operational cost centers are 35% labor and fuel, which is 15% [Ref. 20]. Autonomous operation and machines/AI/robotics vice humans for piloting and service under development would greatly reduce labor costs. The increasing electrification of aircraft for emissionless operation at increasing range, with electricity supplied by ever less expensive renewable energy, utilizing electric motors some 2X more efficient than gas turbines, along with advanced aerodynamics to increase lift to drag ratio by 2X would greatly reduce fuel/energy costs for aeronautics. Printing manufacture and autonomous robotics for manufacture and possibly adhesives should reduce the costs of ownership. Autonomy will also enable the buildout of the huge new aero market in small electric flying machines via autonomous operation of an enabling ATM system for tens of millions of flying things.

The poster child for cost reduction in aerospace is Space X, which, after decades of efforts by others yielding rather minor reductions, has reduced low Earth orbit (LEO) access cost by huge factors. This was accomplished by a combination of reusable stages, printing, automation, and operational cost savings. Going forward, these cost reductions are expected to enable the development of deep space beyond GEO and the colonization of Mars. As AI/autonomous robotics develops, the usual major project cost element, human labor, can be replaced even more by machines. And, with the continued development of AI/robotics, most space operations can be conducted by machines. Humans in space are far more expensive than machines so the resultant cost savings are major. Mars has a huge variety of resources that can be developed given energetics and machines via what is termed in situ resource utilization (ISRU), saving the immense costs of bringing equipage and supplies from Earth, enabling the colonization of Mars, and establishment of an independent Martian economy. A major nearer-term barrier space issue is space debris, for which fuelless removal via tethers could be far less costly than fueled operations. Utilization of advanced nuclear batteries and possibly low energy nuclear reactions (LENR) to power everything in space, enabling reduced weight and separation of propulsive mass and energy (vice combined in a "fuel"), will both change mission architecture options and lower cost.

Energetics – Space faring, including space exploration, commercialization, and colonization, requires major levels of power and energy. They are required for in-space and on-body propulsion, habitats, and transportation, ISRU, manufacturing, life support, robotics, satellites, sensors, and construction. The current power and energy sources being applied and under development include solar energy, chemical fuels, radioisotope thermoelectric generator (RTG) nuclear batteries, and fission nuclear reactors. There are problems with each of these including reductions in solar intensity farther from the Sun and due to dust, ISRU resource processing requirements, storage, transfer of chemical fuels and the weight, energy density, and safety of the current nuclear approaches [Ref. 21]. Alternative energy sources could reduce cost and weight and improve safety, efficiency, and functionality [Refs. 22, 23]. For aeronautics, the historical source of power and energy is chemical fuels. The aeronautical industry has been constrained by their utilization and forced to focus on extreme efficiency to eke out further capabilities. More recently, the climate situation has shifted chemical fuels to those where the CO_2 produced is at least a closed cycle, with no additional CO_2 emitted to the atmosphere. Climate is also leading to development of electric propulsion for aircraft, powered by chemical batteries with their limited capabilities. The outlook for advanced chemical batteries is promising and battery powered electric propulsion is wholly emissionless. The power and energy need for aeronautics includes far greater energy density batteries, including for powering supersonic transports.

Recent research has now proffered going forward another power and energy option for space, exploitation of the nuclear weak force. Nuclear fission is six to seven orders of magnitude greater energy density than chemical. Nuclear fission produces heat, has a specific impulse (I_{sp}) on the order of 1000 secs, which is twice that of chemical.

The new weak force nuclear batteries are light enough to power high thrust magnetohydrodynamic (MHD) rockets that have an I_{sp} in the 6,000 sec and greater range, some 10+ times chemical I_{sp} and 6+ times nuclear fission. There are two extant types of developing weak force energetics. One does not produce radiation, is a heat battery, and is suitable for aeronautical applications, proffering global plus ranges for wholly emissionless electrics and much more, including mitigating climate issues in many ways. The alternative weak force energy source is a solid-state electric battery that scales from milliwatts to tens of megawatts and is 25 times plus lighter than a fission reactor. This electric battery lasts for years and could replace fission nuclear for propulsion and on-body energy needs with scaling capabilities providing distributed, point of use power and energy. Advanced nuclear batteries could also replace solar photovoltaics (PV) for space faring and enable space exploration and exploitation beyond Mars where solar is weak. The overall impacts of the weak force nuclear batteries for aero and space are to provide a state of "energy rich", a unique situation for aerospace, and greatly increased design and architecture parameter spaces including new options to improve acoustics.

Another improving aspect of power and energy is increased thermal to electric conversion efficiency which can yield up to four times the traditional levels. Energy conversion approaches, including sterling cycles and thermal photovoltaics (T-PV), can enable far more widespread utilization of waste heat regeneration in space. This would reduce the size and weight of space radiators for heat rejection. There is also an available breakthrough in space radiators that uses droplets of heat exchanger fluids, controlled by magnetics. This would greatly increase the radiation-to-space heat exchange area and reduce the size and weight of the radiator by factors. The greatest energy density obtainable from the current state of physics is antimatter interaction with matter. This produces some 100% mass to energy conversion and is 9 orders of magnitude times that of chemical energy density. Fission/fusion are two orders of magnitude lower because there is only partial mass to energy conversion. The "cheap" antimatter is positrons or positive electrons, and when interacted with matter produces .5 MEV gamma, which can be thermalized for use. We can store positrons for many minutes thus far, a work in progress with application to deep space propulsion. There are some ultra-high energy density chemical approaches, but they have not yet been deemed safe for usual energetics applications.

Safety – Safety is an issue regarding mission attainment, with the most stringent safety concerns being those associated with onsite humans [Ref. 24 and Refs. therein]. Reliability analysis can be defined as the study of why, how, and when things fail. Safety is what happens when they do fail. Conventionally, reliability involves serious testing and operational experiences and statistics derived therefrom. This approach, as applied to civilian airliners, resulted in a magnificent reliability and safety record, used as the benchmark for the safety of other systems and missions. Aeronautics is now developing advanced air mobility (AAM), which are smallish, electric, mainly VTOL capable, air vehicles now feasible due to the IT and other technical revolutions over these past decades. Included in over 700 versions of AAM vehicles now in development are fly/drive replacements for automobiles or Personal Air Vehicles (PAV). After a century of efforts, "flying cars" are now becoming feasible. The projected markets for AAM and PAV are in the 2+ trillion-dollar range and tens of millions of flying things vice the current tens of thousands. This alters the viability and safety of the current human-centric air traffic control (ATC) system. For space faring, the usual rocket "safety" experiences issues occur after some 100 launches, although Space X is now exceeding that. This safety record is on the order of 1000 times less safe than commercial aircraft, which is the aerospace industry standard.

In aerospace, human factors are responsible for some 90% of safety issues. Therefore, the increasing developments in AI/autonomy that remove direct human involvement for such as ATC, rocket manufacture, launch operations, and much else should provide close to an order of magnitude improvement in safety. The current limited capacity (thousands of aircraft, human operated) ATC system can be non-linear (i.e., smallish changes, occurrences producing large problems, it must always function, and is operated by humans with their associated latency and errors). Morphing the existing system to what will be required for many millions of aircraft is essentially a bridge too far. Ongoing changes to the existing system (e.g., FAA NextGen) are benign compared to what is required for the projected uncrewed aerial system (UAS)/PAV numbers and are taking far too long. The enabling ATC system for UAS/PAV is the major issue impeding the development of these new markets. The vehicle and the safety/reliability issues pale in comparison with the ATC shortfalls. A suggested approach that is better, faster, cheaper, and is an alternative to evolving the existing ATC system, is to develop a giant simulation around the current system, taking data from, but not inputting into or interacting with, the existing system. This simulation is then used to develop requisite software and associated hardware including for communications, navigation, software, sensors, collision avoidance, architectures, and AI. All these piece-parts and their system of systems interact to create a new, wholly autonomous, minimal latency, and fail-safe ATC system capable of handling millions of air vehicles. This simulation could then be physically demonstrated in the desert and once proven, becomes the new ATC system. The existing ATC system is then shut down and replaced by the simulation which is wholly autonomous. Oftentimes the best approach is to start over, especially when there is a plethora of new enabling technologies and vastly altered performance requirements. Those requirements for aeronautics include many orders of magnitude greater numbers of air vehicles and substantial reductions in latency.

What is especially efficacious for space access rocket reliability/safety in the future are the cost reductions from use of reusable rockets, along with considerable further cost reductions from frontier materials/dry weight reductions/greater payload fraction, and use of AI/robotics for end-to-end operations in lieu of human labor. These cost reductions should enable major improvements in reliability and safety to be afforded, developed, and deployed. An issue is determining the level of launch reliability and safety required by the developing commercial deep space businesses. The current 1% or greater loss rate can, and should be, much improved. There are committees to exchange information and develop safety/reliability standards concerning commercial space flight. There is evidently not yet an agreed upon loss of crew (LOC) criteria, nor are there other criteria concerning what is safe enough for commercial space. These are needed to guide further ideation and research and development (R&D) for improving such. Major safety improvement opportunities include greater structural factors of safety and reduced uncertainty, from material characterization and operational conditions to systems of systems back-up, fail-safe systems, extensive sensor suites, in vehicle health management (IVHM), emergency and recovery systems, AI monitoring/solution generation, execution systems of systems/operational aspects/potential hazards, and tipping point identification. Suggested approaches for orders of magnitude increases in safety and reliability include greatly enhanced discovery, collection, and documentation of all hazards going into the design cycle including combinational, cascading failure causes/risks (mechanical, software, environmental, human factors, including extreme cases), and autonomy to largely obviate human factors risks, which are usually the most prevalent cause of serious issues. This requires superb, trusted autonomy technology, ubiquitous instrumentation/data analytics for intuition of developing issues to enable repair and obviation, fail-safe design including hardware and software, greater margins/damage tolerance, and resiliency and analysis/prevention of cascading system failures. Overall, safety and reliability are a prime metric from materials, design through manufacturing, operations, maintenance, monitoring, and throughout the life cycle including at the systems of systems level.

AI - AI has a long, and because of its increasing importance, relatively well-known history. The increasing capabilities of computing including machine speeds, storage, and software has, since the AI "founding" Dartmouth summer study in 1956, resulted in a traverse through classical-looking hype cycles and AI winters in the 1970s through the 1990s. Then, circa 2012, the machines become capable of executing in a useful manner neural nets informed by big data in a process termed deep learning [Ref. 25]. This approach to AI has grown rapidly with regards to capabilities, applications, research scope, intensity, market size, and importance to society across an ever-expanding spectrum of areas and problems. The critical application issue regarding this AI approach is data curation. An example of an important-to-critical application is the ever-increasing shift to decisions by algorithm/AI. In specific arenas, the neural net AI approach has already attained or exceeded human capability and is one of several AI approaches available. There are efforts, termed whole brain emulation [Ref. 26], which date from the IBM blue brain era to nano-section the human neocortex and replicate it in silicon, thereby possibly approaching human level intelligence. Another alternative is the way humans developed intelligence [Ref. 27]. The human brain became complex enough that it "woke up", evolution. The recent observations of "black box" behavior/ideation/production of unique solution spaces by AI via processes opaque to humans [Ref. 28] suggests evolving AI evolutionary intelligence paths going forward are possible and that human intelligence is not unique. AI has a 33% growth rate, a projected market of $190 billion by 2025, and an estimated contribution to the global economy of $15.7 trillion by 2030 [Ref. 29]. AI is ever more capable and being applied to more and more difficult and important applications [Ref. 30]. There are now computers specifically designed and optimized for AI applications. The number and extent of the applications include E-commerce, education including virtual instructors, autonomous vehicles, personal advisor, robotics, human resources including hiring, health care, agriculture, gaming, marketing, finance, search, cyber security, national security, manufacturing and increasingly smart everything. In technology and engineering, AI is the enabler for autonomy, data analytics, and knowledge management, translation of 75% of research which is outside the U.S., and increasingly important for sensing, image processing, cyber-physical systems, the internet of things, self-organizing systems, optimization, cost reduction in manufacturing and operations, decisions by algorithm, software engineering, and safety (e.g., Ref. 31). The aerospace applications of AI include autonomous aircraft, ATM and space operations, smart everything, manufacturing, operations, simulations, safety and cost reductions, optimization, and efficiency.

AI can now ideate better than humans in some respects and "knows" more than humans. AI enables autonomous systems that can greatly reduce the costs of onsite humans for both aero and space. In space humans are orders of magnitude more expensive, and for aero, AI/autonomous systems are required for both vehicle operation and ATC to enable the buildout of the 2+ trillion-dollar AAM/PAV markets involving tens of millions of flying things. Autonomous systems could, now or going forward (compared to human operation) [Ref. 32], know far more, be less expensive, exclude operational human error, have far less latency, provide new functionalities, have far longer duty cycles, provide size reduction(s), be faster and more efficient, be far more durable and "patient" and operate at conditions and performing functions where and in a manner that humans could not. As AI is developing, the machines are replacing humans in an increasing number of jobs, including in aerospace. The affordable and safe development of humans in space, including deep space beyond GEO, commercial deep space, colonization of Mars, and the AAM/PAV aero buildout requires "trusted autonomy". This is autonomy that can function independently of human interaction, i.e., humans trust their lives and fortunes to this technology. Aero has long employed autonomous systems but kept pilots if humans are aboard because human pilots were considered better with regard to unknown unknowns and untoward events. Now that AI can ideate via evaluation of huge numbers of quasi-random combinatorials, they can increasingly deal with unknown unknowns and thus ensure the timely development of huge new markets in AAM/PAV and commercial space including deep space.

Tele-everything - Real-time human interaction at a distance has evolved over time from the telegraph to the telephone to early video and, in the last few years, to augmented reality, virtual/digital reality, and holographic projections, all of which provide degrees of immersive presence. Today, we have early forms of telecommuting, teleworking, teleshopping, teleeducation, telemedicine, telepolitics, telemanufacturing, telecommerce, and teletravel. Taken together, we are witnessing early development toward virtual worlds satisfying all five human senses, aka the "metaverse". The tele-everything milieu is headed toward sophisticated immersive presence, with potentially profound impacts for air travel and human space exploration [Ref. 33]. Teletravel appears to present a significant reduction in the demand for long-haul air travel with a concomitant impact on the need for aircraft research and development work. Digital reality and immersive presence technologies are increasingly less costly with increasing bandwidth, storage, and computing speeds. Also, significant progress has been made regarding brain-to-machine communications. With these improvements, the technologies are becoming serious competitors to physical business travel and, increasingly, leisure travel. During COVID, the associated shift for health reasons to virtual presence utilizing extant, early days yet technology resulted in greater worker productivity and studies indicate virtual conferences have greater attendance and productive "virtual hallway" interactions. The benefits of teletravel over physical travel are many and include social distancing/working from home during pandemics, major cost reductions and time savings, less time spent in airline security lines and less hassle overall, being anywhere at any time with possibility of multiple contacts/places/meetings on a given day, lack of physical and health risk, no overcrowded sites/venues, greatly reduced CO_2 emissions and thin cirrus clouds which are climate forcing, the infirm can enjoy the thrill of travel, and access to superb educational experiences all with current technology enabling nonverbal/body language communications. A sizable acceleration of the ongoing shift from physical air travel to digital reality, if it indeed occurs, would affect the economic health of the air transport industry, from research to construction of the necessary infrastructures and vehicles. However, there would still be a healthy air cargo industry, and to-be-determined additional impacts on the nascent development of unmanned air systems, urban air mobility aircraft, and personal air vehicles with their short stage travel lengths. A virtual leisure travel industry is developing. This industry provides virtual tourism as an alternative to physical tourism. Along with the many benefits of digital reality already discussed, they offer virtual trips to destinations without the crowding that's increasingly prevalent for physical travel, along with adventures that are not physically possible, such as realistic travel to historical places as they existed in previous ages. This virtual tourism industry has shown good growth, especially during the pandemic. Similar success has been observed regarding virtual business conferences, allowing many more people to attend and with no venue costs or scheduling issues. Thus far, there do not appear to be major downsides associated with teletravel. We started out traveling across the country on horseback, then on trains and aircraft, ever gaining more speed until finally we are now transporting ourselves with electrons as an immersive, digital presence. Humans have twice before altered much their societal situation, hunter-gatherer to agriculture and agriculture to industrial. We are now altering yet again as we leave the IT age and enter the virtual age, becoming cyborgs to an ever-greater extent with brain chips and direct brain-to-machine communications.

Aeronautical Barrier Issues

ATM for Tens of Millions of Flying Things - In the late 1900s, civilian air transport consisted of commercial scheduled airlines and general aviation using small aircraft that were piloted by humans. Since then, various technology revolutions and their impacts upon technical capabilities, miniaturization, and cost reductions have enabled a third component of civilian aviation termed AAM, Advanced Air Mobility, Drones, or Uncrewed Aircraft Systems (UAS), with a prospective market value above $2 trillion per year [Ref. 34, 35]. AAM is on a very fast growth track, with burgeoning applications for service, government, science, commercial missions including delivery, inspections, agriculture, mapping, search, and rescue, firefighting, border patrol, law enforcement, conservation, real estate, and more. It also enables the realization of a century long dream of aviation: affordable and safe personal air vehicles to transport humans. Before AAM, civilian aircraft were piloted by humans and numbered in the thousands. AAM vehicles number in the millions even now and their numbers are realistically headed into the many tens of millions, especially as they replace automobiles. Enabling technologies will increase UAS capabilities and drive down costs still further. There are currently over 700 AAM vehicle designs in development. The low cost of these new aviation machines is projected to result in many tens of millions of them taking to the skies. Most of them will operate over developed and populated areas, potentially posing a safety concern [Ref. 36].

At this juncture, the major issues with rapid development of these new aviation markets are non-vehicle specific infrastructures including landing/takeoff areas, especially in urban regions, and, most importantly, safety and access to the air space [Ref. 24]. The current consensus appears to be that, while nearer term modifications and additions will aid air traffic management for the initial introduction of UAS and Urban Air Mobility (UAM) the current system [Ref. 3], which is very difficult, costly, and time consuming to modify, cannot scale, and lacks the latency to enable tens of millions of flying things [Ref. 37]. The latency issue revolves around the human-controller-centered nature of the current ATM systems. Worldwide, the current, nearer term AAM-centric ATM approaches address the problem via adding a low altitude system for UAS while keeping the current mid and higher altitude ATM systems. Going forward, the buildout of UAS will include vehicles flying in what is now legacy ATM mid to above altitudes. Therefore, a single system for all altitudes appears to be required going forward.

The foremost requisite of such a new system for AAM/PAV is autonomy, both for the ATM system and the air vehicles. This is the only approach that can scale to tens of millions of flying things in controlled air space. Such a single system should obviously be scalable to the tens of millions level and be inexpensive to develop, install, and operate. It must be operational in the time frame of the market's needs for a single system and operable at the tens of millions level of use. The other major requirement is safety and security, specifically in terms of accidents and electron vulnerabilities including cyberattacks, Electro-Magnetic Pulses (EMP), and jamming. The requisite components (on board and on the ground/in space) of such a single ATM system for tens of millions include navigation that is fail-safe to GPS jamming, sensors, collision avoidance, trusted autonomy, detection, and control of noncooperating air vehicles, resilient communications, an architecture that involves cooperative information sharing across all components, and the requisite AI and computational equipage. For the longer term with tens of millions of flying things, a new single autonomous ATM system is required. It should be capable of rapid and inexpensive development. Evolution of the current ATM would take far longer and cost far more than the approach described herein because of the human operated systems that, even if morphed into autonomous operation, must continuously function in the process. This is evidenced by the many years and much treasure required to modify it for "Next Gen" capabilities, a pale shadow of what will be required for the AAM/PAV buildout. The nominal time frame for such a new system to go live should be the order of five to 10 years, dictated by the rapidly evolving AAM markets which will require air space access for a $2 trillion-dollar new aero market, including replacing automobiles.

One approach is to build a giant simulation around the current ATM system(s), extracting data from them for development, but not changing them in any way, at least initially. The initial development of such a simulation began in the NASA "Smart NAS (National Air System)" effort [Ref. 37]. Step two is development of each of the related requisite functionalities noted above in the simulation, followed by further development at the system of systems level, always keeping fail-safe design in mind. Then, virtually stress-testing the operation of the new ATM system developed in the sim, followed by physical testing in the desert would need to be completed. Once the new system is physically certified, the existing system is then turned off and the sim becomes the new ATM system. The development of such an autonomous system is discussed in ref. 38.

Emissionless Aircraft [Refs. 39, 40] – Climate change issues have become sufficiently obvious and serious that there is increasing concern regarding the contribution of aircraft emissions to adverse climate impacts. Major aircraft emissions include CO_2, water, and nitrogen oxides (NO_x) from combustion of fossil fuels. CO_2 can be seriously reduced by switching from fossil fuels to biofuels, green hydrogen, or green hydrocarbons produced using renewable energy. However, there would still be water and NO_x emissions. The only truly emissionless in-flight aircraft propulsion is stored electricity turning very efficient electric motors. The current state of the art of battery electric storage enables an emissionless stage length of 400 to 500 miles, which is nearly half of aircraft trips but far less than half the CO_2 emitted. Battery technology is advancing rapidly, with two to three times current energy density in development and advances in lithium/air batteries with 7X energy density becoming more feasible. The latter would increase the available emissionless stage length to the order of 3,200 miles. Advanced aerodynamics concepts appear to proffer a doubling of lift to drag (L/D) ratio, which would increase the emissionless stage length further to the order of 6,000 miles plus, obviating a very high percentage of the aircraft emitted CO_2.

Cost of biofuels utilizing halophytes, salt plants that grow on deserts, wastelands utilizing saline or seawater, would be low and the production capacity massive, without the use of arable land and fresh water. Forty-four percent of the Earth's land mass is wastelands, deserts, and 97% of the water is saline or seawater. Wastelands and deserts are sunny for the most part, providing cheap renewable photovoltaic (PV) energy for pumping water. The halophyte biomass provides the feedstock for plastic pipes. Hydrogen has many issues including cost, corrosiveness, transport, and storage difficulties including increases in wetted area and drag, some safety concerns, has low generation efficiency, and produces more water emissions. Due to its corrosiveness, hydrogen is not usually a direct drop-in fuel. Biofuels, termed sustainable aviation fuels (SAF), and green hydrocarbons, are usually drop ins. Going to electric propulsion, whether using batteries, including the new Japan-developed LENR heat batteries or fuel cells, changes the propulsion device from a gas turbine or internal combustion engine to electric motors that have far less maintenance and twice or more the efficiency.

The approaches to substantially increase lift over drag (L/D) involve both major aircraft drag components, drag-due-to-lift (~ 35% of total drag) and friction drag (50% of total drag). An external wing truss would enable major reductions in both drag components. A truss would allow a doubling of the wingspan which could reduce drag due to lift up to 75%. Wing hinges to enable continued use of 80-meter boxes at the airport gates have been designed. The external truss would also then result in halving the wing chord, cutting the Reynolds number in half, and enabling far lower wing sweep, low enough to obviate crossflow boundary layer instability and proffering large regions of "natural"/pressure gradient laminar flow/lower skin friction on the wing. There are developments regarding plasma drag reduction for turbulent flow that could be considered for production of sizable fuselage skin friction. Also, moving the engines to the rear of the fuselage and using thrust vectoring for control would obviate the drag and weight of the empennage. Overall, studies by Pfenninger and Virginia Tech such ideas indicated doubled and more lift to drag levels.

Acoustics – Over time, aircraft acoustics issues have both become more prevalent with increased air traffic, and less worrisome via such improvements as high bypass engines. However, the emerging AAM market buildout, including massive numbers of PAV vehicles popping up from driveways and streets, could create greatly increase societal acoustic annoyance. This will require enhanced design attention to acoustics, making it one of the fundamental design metrics. For VTOL operation, the prime noise sources are engine, transmission, airframe, lift, controls, and propulsion. Going electric largely obviates engine and transmission noise, leaving lift, propulsion, airframe, and controls noise, of which lift is the dominant source. The major historical approaches and technologies for VTOL operation, rotary wing, and powered lift are noisy, and major acoustic quieting R&D has been and is required to ensure PAV societal acceptance and marketability. One approach to reducing AAM acoustics significantly would be the utilization of developing new energy sources, e.g., lithium/air batteries and LENR which would enable "energy-rich" design and operation and reduced disk loading on the rotors, becoming larger, multi-bladed, and slower turning. The electric VTOL (EVTOL) designs are already replacing noisy combustion propulsion with far quieter electric motors and utilization of dynamic active shape control and motions to reduce such as blade-vortex interaction noise. Overall, the lower the weight/drag, the quieter the vehicle. Therefore, improved materials (e.g., nano scale printing) to reduce dislocations and grain boundary issues would contribute to quieting, as would frequency shifting and configuration designs producing noise “shielding”. The major “new” quieting approach going forward is becoming energy rich via either advanced batteries or the new weak force heat batteries with energy densities 10,000 times that of chemical energy density to enable economical operation at quieter lower component efficiency levels.

AAM/PAV Infrastructures - The most important infrastructure required for the buildout of the AAM/PAV markets is an autonomous ATM system. The system would interact with autonomous AAM/PAV vehicles and would be capable of dealing with tens of millions of flying things popping up from neighborhoods, as already discussed. The energetics infrastructures to recharge the batteries or LENR devices will be increasingly distributed going forward, “rooftop” solar/wind/etc. storage locally, vice central grids and generation. Going forward, landing and takeoff will be local also instead of at central airfields. The advanced batteries or LENR will enable “energy-rich” designs to power vehicles less efficient than cruise flight designs, which is a requisite for such dense, distributed operations. Energy-rich and vectored-thrust or flow control would greatly decrease weather related issues. The all-important cyber and communications infrastructure required by the huge traffic numbers and co-operative autonomous operations is perhaps of greatest concern of all the infrastructures. There is less than secure protection of IT from EMP, either due to solar storms or terrorism, and cyber security is a work in progress. Overall, the envisaged distributed operations and energy generation in the AAM/PAV buildout will greatly alleviate current concerns for security of the energy supply and reduce the current perceived need for “vertiports”. However, distributed operations of this nature require serious quieting and flow control to avoid societal disturbances of various natures.

Space Barrier Issues

Galactic Cosmic Radiation (GCR) - Space radiation present both in space and on planet/body causes radiation sickness, degenerative tissue effects, DNA damage, DNA repair process alterations, oxidative DNA damage, immune system degradation including significantly reduced ability to produce blood cells, anemia, carcinogenesis including leukemia, tissue degeneration, respiratory effects, cataracts, heart, cardiovascular and digestive system impacts, neurologic effects, central nervous system, and cognitive impairment, Alzheimer’s precursor (white matter hyperintensities of the brain) reduced length and area of dendrites, performance decrements and memory deficits, loss of awareness, focus, and cognition, and collateral tissue damage to adjacent cells (called bystander cell damage from heavy nuclei), which could increase the cancer risk by some factor (Ref. 41). There are three approaches to radiation mitigation that can be employed combinatorially: Spend less time in space, shield or deflect the incident radiation, and biological/medical counter measures to mitigate the resultant health impacts. In general, shielding requires low atomic number 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 humans. The latter may be able to provide protection while in space suits, albeit this may require an exoskeleton to carry the weight/handle the inertia, etc.

Overall, due to systems level and conceptual/technological breakthroughs, the outlook for GCR radiation mitigation has altered over these last years from problematical/unaffordable to several potentially viable solution spaces across the technology readiness level (TRL) spectrum [Ref. 16]. These breakthroughs include inexpensive space access via reusable rockets, a low kg/kW (Alpha) many MW class nuclear battery, high energy particle reflection via silicon crystals, and the synthetic biology/gene editing revolution as applied to biological/medical countermeasures.

In decreasing order of TRL:

For on moon, planet etc., ~ three meters of regolith

For in space:

- Fast transits (200-day round trips to Mars) via inexpensive chemical fuel
- Three-meter reusable polyethylene spacecraft overcoat with increased feasibility via inexpensive chemical fuel
- Biological/medical countermeasures - a partial solution in space thus far, with effectiveness improving
- Fast transits (200-day Mars round trip) via 6,000 sec. I_{sp} variable specific impulse magnetoplasma rocket (VASIMR) high thrust MHD propulsion powered by an alpha of order one nuclear battery

- Magnetic redirection of GCR particles via superconductive (S-C) magnets located extended distances from the spacecraft
- Silicon crystal reflection of GCR particles plus shielding for Gamma secondaries

All these approaches require extensive research and optimization with subsequent triage and development to determine the most efficacious for development/utilization. The current unsatisfactory status of GCR mitigation makes such investment necessary due to GCR being the agreed upon most serious human health deep space exploration/colonization issue.

Space Debris - What goes up must come down... except when it doesn't, when it is put into orbit with too little drag to bring it down in a reasonable timeframe. We have been putting satellites up, along with rocket piece-parts, since the late 1950s. Thousands of them are still up there. There have been explosions in space and many collisions, two of them serious major events. All of this has contributed to the current large space debris population, the amount of which is daunting, with sizes from meters to mm or less. Even the smaller pieces, given the closure speeds, can create worrisome effects upon impact. As an example, an impact speed of 12 km/sec has approximately 10 times the energy density of dynamite. In the literature, the cascading of collisions producing ever more debris until the space region is essentially unusable is termed the "Kessler Effect." The major and increasing worldwide reliance upon space assets–our "positional Earth utilities"– has made space debris an increasingly serious problem. Then there are the plans and progress to put up 50,000 low earth orbit (LEO) satellites to provide high speed internet and optical "staring" via hopping satellite to satellite. The space debris is interfering with the launching of these, and other satellites and the developments of commercial deep space. Solutions to space debris are obviously required. Progress regarding this has thus far been focused on both "detect and avoid" (becoming increasingly problematical) and designing new satellites to be self-deorbiting after reasonable time periods. However, due to several issues, mainly cost but also some legal concerns, physical removal of extant space debris is still in a very early experimental stage, with costly projections for execution [Ref. 42].

The major reason for the high cost of debris removal is the perceived necessity of employing fueled debris retrieval. There is, however, an alternative to that: powered electromagnetic tethers [Ref. 43]. The Earth has a magnetic field that powered tethers could use to alter altitude and position in space given energy from solar or high energy density nuclear batteries. No propulsive mass is needed. Fuel is a combination of propulsive mass and energy. With the magnetic field enabling propulsion, only energy is needed. This reduces most of the up mass, which is the fuel weight required to retrieve and clean up debris. Estimates of debris cleanup cost savings are as high as 96%, some 4% of the cost of fueled approaches. Once retrieved with the tether approach, instead of attaching unpowered tethers to deorbit the debris it could be moved to a space junk yard for reuse, repurpose, both piece-parts and the materials. Such reuse of debris could perhaps foster in-space manufacture and repair.

Affordable and Safe Humans to Mars - The fundamental differences regarding the Moon vs. Mars for humans include far longer missions and the greater resources required for Mars. In humans-to-Mars planning, thus far the extant technologies and approaches have not enabled missions that are both fully safe/healthy for humans and affordable [Ref. 44]. Cost reductions are required to afford health and safety and to reduce their costs overall. The major cost centers are nominally space access, in-space round trip, habitats, on-surface operations and development, facilities, operations, and support. For cost reduction considerations, these cost centers can be addressed as individual issues and combinatorially at the systems, configuration, and architecture level. Some technologies and approaches can reduce the trip/on planet per se costs, some can reduce the costs of approaches to ensure greater crew health and safety, and some can do both. The combination of these cost reduction approaches would result in humans-to-Mars being far more affordable, safer, and healthier. The following posit serious cost reductions but often require major changes in technology and mission planning [Ref. 44].

<u>Make it there, instead of taking it there</u> – Mars has a vast array of resources including nickel, titanium, iron, sulfur, magnesium, calcium, phosphorus, chlorine, bromine, aluminum, silicon, oxygen, hydrogen, carbon, nitrogen, sodium, manganese, potassium, chromium, and deuterium. Overall mission costs scale to the requisite mass launched into LEO. Nominally for initial small-crew missions such as Apollo, they take everything needed, which is some 900 metric tons. Much of this could, via sending autonomous robots years before the humans, go on inexpensive slowboats propelled by various varieties of sails, and/or can be produced via ISRU. This includes fuels

and propulsive mass that is checked out at on-planet conditions before the humans get there. The expensive tonnage is then much reduced.

Being Energy Rich – Much of the requisite tonnage is associated with power and energy. Switching to new high-energy-density nuclear batteries, such as the ones under development and experimentation at NASA, would greatly reduce the weight associated with power and energy and enable energy rich operation of essentially everything along with much greater mission flexibility and safety. This enables atmospheric-breathing powered entry, descent, and landing (EDL) to greatly improve safety and reduce cost of such. It also enables microwaving regolith to release water for life support, fuels, and plastics along with powering refrigeration to solve the cryogenic fuel storage boiloff problem, as examples.

Fast Transits – Very inexpensive chemical fuels could, via brute force, greatly reduce the in-space transit times. Variable Specific Impulse Magnetoplasma Rocket (VASIMR), a high thrust Magneto Hydrodynamic (MHD) propulsion approach with a specific impulse (I_{sp}) greater than an order of magnitude better than chemical and powered by nuclear thermionic avalanche cells (NTAC), could enable 200-day Earth-Mars-Earth round trips, which would be very fast transits. Such fast transits largely "solve" in-space micro gravity and radiation health issues for humans-to-mars, reduce logistics quantities, increase reliability, and reduce costs.

"Ditch and Bury" – Inflatable, rigidizable habitats buried under some four plus meters of regolith for radiation and micrometeoroid protection and thermal insulation would obviate freighting expensive, heavy surface habitats with inadequate radiation protection.

Cheap space access - The breakthroughs regarding serious space access cost reductions are due to SpaceX and their pioneering development of reusable rockets, along with reduced manufacturing and operational costs [Ref.5] Factors of 6x to 14x cost reductions are being discussed, with projections for the SpaceX Starship of 100 metric tons for $2 million, some $10/lb. to orbit, far below the usual thousands of dollars per pound. Even greater values may be in the offing from continued artificial intelligence (AI) developments and subsequent further replacement of expensive human labor by autonomous robotics, along with increased launch rates providing economies of scale. Also, the efforts involving material printing at the nano scale to produce a much better material microstructure may enable reduced dry weight and payload weight, providing additional cost reductions. Additional cost reductions approaches are given in Ref 44.

Communications – Space communications are shifting to optical for greater bandwidth. There is, however, a nascent communication approach that eschews electro-magnetic (E-M), utilizing the quantum vector/ scaler potentials for communication (e.g., Ref. 45). This approach uses Scalar Waves only, E-M fields suppressed/canceled. It is penetrating and non-shieldable, the far field decays as 1/r (range or distance) vice $1/r^2$, requires Quantum Detectors (e.g., Josephson Junctions), is non-detectable by ordinary E-M devices, and enables high bandwidth comms through the air-water interface. The theory comes from the work of Aharonov and Bohm. The approach mitigates many E-M communication system interference issues including dust, plasma, and water. It provides unique security, dependability, and resiliency.

Entry, Descent, and Landing (EDL) – for bodies without atmospheres, EDL is straightforward and is a variant of powered retro descent. However, for bodies with atmospheres the spectrum of EDL approaches is far richer. Utilizing the atmosphere to the extent possible for deceleration reduces mission costs and weight to a significant extent. EDL atmospheric utilization approaches include parachutes, inflatable aeroshells to increase drag area at low weight, lifting aerodynamics to add drag due to lift and increased time in the atmosphere to accrue drag, regenerative aerobraking, taking in atmosphere constituents and energy to utilize at lower altitudes, plasma/magnetics, and aerocapture. The development of low weight/high energy density power sources such as NTAC and LENR [Ref. 22] increases the EDL option set significantly. Being "energy-rich" enables heating and retro ejection of ingested atmospheric constituents during entry. Also, increasing passage I_{sp} by a factor of 12 via NTAC powering of VASIMR results in a far lower cost for fuel for powered retro ED, as does the SpaceX huge cost reductions for LEO access, providing "cheap chemical fuel". Systems level issues and metrics are necessary to evaluate which/what of a now very rich collection of EDL approaches are most beneficial for critical issues such as landing large, human requirements-level payloads on bodies with rarefied atmospheres such as Mars.

Concluding Remarks

This summary of advanced ideas and solution spaces for a spectrum of substantive issues and barriers in aerospace is an update to a series of three NASA TMs circa 2012-2014 written with the same purpose, the three covering aeronautics, space, and aerospace, respectively [Refs. 46– 48]. Both aeronautics and space have changed considerably in the ensuing eight to 10 years regarding technology and barrier issues. SpaceX, reusable rockets, and other technologies have and are still greatly reducing the costs of space access. This in terms of econometrics opens deep space for commercial activities and is a major enabler for making humans-to-Mars travel both safe and affordable. Another major, currently nascent technology change affecting aero and space capabilities and markets is the development of nuclear weak force energetics at 10,000 times chemical energy density. The ongoing development and success of AI is enabling autonomous robotics, essential in aero for a $2.5 trillion buildout of AAM/PAV and positing huge savings in space operations where robotics are two or more orders of magnitude less costly than onsite humans. The very success of space developments has created a rapidly increasing barrier, space debris, requiring further low-cost technology ideation and development to mitigate. Humans-to-Mars, involving far longer than the usual six months in LEO and twice the GCR level, has placed a premium upon addressing reduction of human exposure to such radiation. The greatly increased impacts and concern regarding climate change has shifted aero focus from CO_2 mitigation to emissionless aircraft. The massive new developing aero AAM/PAV markets are pioneering renewable-energy-powered electrical propulsion. Overall, aerospace is in a very different place with different opportunities and barrier issues than it was a decade ago. This report addresses advanced, orthogonal in many respects, solution spaces for current aerospace barrier issues to enable more economical and safe solutions to problems, such as the AAM/PAV aero buildout, emissionless aircraft, humans-to-Mars (as both safe and affordable), and accessibility for commercial deep space.

References

1. Hansen, James R., "The Bird Is on The Wing", Texas A & M University Press, 2004.
2. Bugos, Glenn E., "The History of The Aerospace Industry", E.H..net [Economic History Association], https://eh.net/encyclopedia/the-history-of-the-aerospace-industry/.
3. Air Transport Action Group, "The Economic and Social Benefits of Air Transport", ICAO, 2005, https://www.icao.int/meetings/wrdss2011/documents/jointworkshop2005/atag_socialbenefitsairtransport.pdf.
4. FAA, "The Economic Impact of Civil Aviation on the U.S. Economy", January 2020, https://www.icao.int/meetings/wrdss2011/documents/jointworkshop2005/atag_socialbenefitsairtransport.pdf.
5. Dick, Steven J., "Historical Studies of The Societal Impact of Spaceflight", NASA, 2016.
6. Raitt, David et al., "The Impact of Space Activities on Society", ESA BR-237, 2005, https://www.esa.int/esapub/br/br237/br237.pdf.
7. Bushnell, Dennis M., "Low to Emissionless Air Transport Design", NASA/TM-20210021985, 2021.
8. Bushnell, Dennis M, Futures of Civil Air Transportation Including Personal Air Vehicles", NASA/TM-20210023715, 2021.
9. IATA, "Future of The Airline Industry 2035", 2018, International Air Transport Association, https://en.calameo.com/books/006960148b88d60eb88e6.
10. Transportation Research Board, NASEM, "Critical Issues in Aviation and The Environment 2021", Transportation Research Circular Number E-C271, May 2021.
11. Aglietti, Guglielmo, S., "Current Challenges and Opportunities for Space Technologies", Frontier Space Technology, 16, June 2020, https://www.frontiersin.org/articles/10.3389/frspt.2020.00001/full.
12. Rose, Frank A., " America In Space: Future Visions, Current Issues", Brookings, March 14, 2019, https://www.brookings.edu/testimonies/america-in-space-future-visions-current-issues/.

13. The White House, "United States Space Priorities Framework", Dec. 2021, https://www.whitehouse.gov/wp-content/uploads/2021/12/united-states-space-priorities-framework-_-december-1-2021.pdf.
14. Bushnell, Dennis M. and Moses, Robert W., "Commercial Space in The Age of "New Space", Reusable Rockets and the ongoing Tech Revolutions", NASA/TM-2018-220118, 2018.
15. Bushnell, Dennis M. and Moses, Robert W., "Perspectives in Deep Space Infrastructures, Development, And Colonization", NASA/TM-2020 – 220442, 2020.
16. Bushnell, Dennis M., "Futures of Deep Space Exploration, Commercialization, and Colonization: The Frontiers of The Responsibly Imaginable", NASA/TM – 20210009988, 2021.
17. Malleboina, Adinarayana, "Why the Aerospace Industry Needs to Use "Should Costing"", Industry Week, Oct. 20, 2011, https://www.industryweek.com/finance/software-systems/article/21941478/why-the-aerospace-industry-needs-to-use-should-costing.
18. Leithem, Scott and Soden, Richard, "Reducing Cost in Satellite Development Through a Holistic Approach to Device Test". Design World, Dec. 7, 2017, https://www.designworldonline.com/reducing-cost-in-satellite-development-through-a-holistic-approach-to-device-test/.
19. Wertz, James, "Commentary/Reinventing Space: Dramatically Reducing Space Mission Cost", Space News, Feb. 4, 2013, https://spacenews.com/reinventing-space-dramatically-reducing-space-mission-cost/.
20. Beers, Brian, "Which Major Expenses Affect Airline Companies?", Investopedia, December, 2021, https://www.investopedia.com/ask/answers/040715/what-are-major-expenses-affect-companies-airline-industry.asp.
21. Johnson, Ben, "Power Sources for Space Exploration", Stanford University, Dec. 2012, http://large.stanford.edu/courses/2012/ph240/johnson1/.
22. Bushnell, Dennis M. et al., "Frontiers of Space Power and Energy", NASA/TM- 20210016143, 2021.
23. Bushnell, Dennis M., "Summary of Frontier Energetics", NASA/TM – 20210026699, 2021.
24. Bushnell, Dennis M. and Moses, Robert W., "Reliability, Safety, and Performance for Two Aerospace Revolutions – UAS/ODM And Commercial Deep Space", NASA/TM – 2019 – 220274, 2019.
25. Anyoha, Rockwell, "The History of Artificial Intelligence", Aug. 28, 2017, Harvard Univ., Science in The News [SITN], https://sitn.hms.harvard.edu/flash/2017/history-artificial-intelligence/.
26. Sandberg, Anders and Bostrom, Nick, "Whole Brain Emulation, a Roadmap", Technical Report 2008-3, 2008, Oxford University Future of Humanity Institute, https://www.fhi.ox.ac.uk/brain-emulation-roadmap-report.pdf.
27. Hofman, Michel A., "Evolution of the Human Brain, When Bigger Is Better", Frontiers of Neural Anatomy, 27 March, 2014, https://www.frontiersin.org/articles/10.3389/fnana.2014.00015/full.
28. Bogdan, "What Is Black Box in Machine Learning", YSBM Group, Software Engineering, Nov. 28, 2019, https://y-sbm.com/blog/black-box-in-machine-leraning.
29. Todorov, Georgi, "65 Artificial Intelligence Statistics For 2021 and Beyond", Feb. 26, 2021, Semrush Blog, https://www.semrush.com/blog/artificial-intelligence-stats/.
30. Marsner Technologies, "The Current State of AI", https://marsner.com/blog/the-current-state-of-ai/#:~:text=Artificial%20intelligence%20(AI)%20has%20become,extracting%20insights%20from%20big%20data.
31. Biswal, Avijeet, "AI Applications: Top 14 Artificial Intelligence Applications in 2022", Simplilearn, 21 Jan. 2022, https://www.simplilearn.com/tutorials/artificial-intelligence-tutorial/artificial-intelligence-applications.
32. Bushnell, Dennis M., "Enabling Electric Aircraft Applications and Approaches", NASA TM-2018-220088, 2018.
33. Bushnell, Dennis M., The Coming Digital Reality", Aerospace America, June 2020, pp. 22 – 23.
34. Thippavong, David P., et al., "Urban Air Mobility Airspace Integration Concepts and Considerations", AIAA 2018 – 3676, 2018.
35. NASEM, "Advancing Aerial Mobility, A National Blueprint", National Academy Press, 2020, Washington, D.C.
36. Brittain, Marc and Wei, Peng, "Autonomous Air Traffic Controller, A Deep Multi-Agent Reinforcement Learning Approach", arXiv: 1905.01303v1, 2 May 2019.

37. Palopo, Kee, et al., “Shadow Mode Assessment Using Realistic Technologies for the National Airspace System [Smart NAS] Test Bed Development”, AIAA 2015 – 2794, June 2015.
38. Bushnell, Dennis M., “ATM For Millions of Flying Things: An Alternative Approach”, NASA/TM – 20205010812.
39. Bushnell, Dennis M., “Ultra-Low to Emissionless Air Transport Design”, NASA/TM – 20210021985, 2021.
40. Bushnell, Dennis M., “Emissionless Air Travel”, Aerospace America, July/August 2022, pp. 32 – 35.
41. Moses, Robert W. et al., “Maintaining Human Health for Humans-Mars”, AIAA Paper 2018 – 5360, 2018.
42. Bushnell, Dennis, “Cosmic Beachcombing”, Professional Pilot, Dec. 2017, pp. 12 – 14.
43. Pearson, Jerome, Joseph A. Carroll, and Eugene M. Levin, "EDDE Spacecraft Development for Active LEO Debris Removal," Paper IAC-14, A6,6.4x23806, 65th International Astronautical Congress, Toronto, Ontario Canada, 29 September-3 October 2014.
44. Bushnell, Dennis M., “Approaches to Humans-Mars Both Safe and Affordable”, NASA/TM 20220007320, July 2022.
45. Puthoff, Harold E., “Communications System”, U.S. Patent No. US 10,992,035 B1, April 27, 2021.
46. Bushnell, Dennis M., “Emerging Options and Opportunities in Civilian Aeronautics”, NASA/TM – 2012 – 217759, 2012.
47. Bushnell, Dennis M., “Advanced to Revolutionary Space Technology Options – The Responsibly Imaginable”, NASA/TM – 2013-217981, 2013.
48. Bushnell, Dennis M., “Frontier Aerospace Opportunities”, NASA/TM – 2014 – 218519, 2014.