

NASA/TM-2019-220274



Reliability, Safety, and Performance for Two Aerospace Revolutions - UAS/ODM and Commercial Deep Space

*Dennis M. Bushnell and Robert W. Moses
Langley Research Center, Hampton, Virginia*

April 2019

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>
- E-mail your question to help@sti.nasa.gov
- Phone the NASA STI Information Desk at 757-864-9658
- Write to:
NASA STI Information Desk
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199

NASA/TM-2019-220274



Reliability, Safety, and Performance for Two Aerospace Revolutions - UAS/ODM and Commercial Deep Space

*Dennis M. Bushnell and Robert W. Moses
Langley Research Center, Hampton, Virginia*

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

April 2019

The use of trademarks or names of manufacturers in the report is for accurate reporting and does not constitute an official endorsement, either expressed or implied, of such products or manufacturers by the National Aeronautics and Space Administration.

Available from:

NASA STI Program / Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199
Fax: 757-864-6500

Table of Contents

ABSTRACT.....	3
INTRODUCTION.....	3
CURRENT CAUSES OF SERIOUS SAFETY AND RELIABILITY ISSUES FOR AERONAUTICS AND SPACE.....	5
RELIABILITY AND SAFETY PRECEPTS/ HAZARDS APPROACHES.....	6
ENABLING UAS/ODM	9
UNMANNED AIR SYSTEMS (UAS)/ON DEMAND MOBILITY (ODM) ISSUES.....	9
TOWARD CRASH PROOF UAS/ODM.....	11
UAS/ODM REQUISITE/ENABLING ATC SYSTEM	12
UAS /ODM PERFORMANCE ENHANCEMENT APPROACH	12
ENABLING COMMERCIAL DEEP SPACE	14
COMMERCIAL SPACE PLANNING/POSSIBILITIES	15
COMMERCIAL DEEP SPACE ISSUES	16
HUMAN HEALTH ISSUES IN SPACE (REF. 3 AND REFS. THEREIN).....	16
IDENTIFIED UNMITIGATED HUMAN HEALTH ISSUES IN SPACE.....	16
MITIGATION APPROACHES FOR HUMAN-MARS HEALTH ISSUES.....	17
SPACE DEBRIS (REF. 4 AND REFS THEREIN)	18
SPACE RELIABILITY/SAFETY STATUS AND PROSPECTIVE WAYS FORWARD	19
POTENTIAL MISSION ANALOGS FOR PRACTICAL APPROACHES TO VERIFICATION OF SAFETY AND RELIABILITY	20
TEST LIKE YOU FLY.....	20
CERTIFICATION STRATEGY BUILT ON PHASED PIECES OF INCREASING COMPLEXITY	21
CONCLUDING REMARKS.....	22
REFERENCES	23

Abstract

Aerospace is in the midst of a renaissance, expanding on both the air and space side into major new commercial areas including unmanned air systems (UAS), on demand mobility (ODM), personal air vehicles (PAV), and commercial deep space. These new areas require, in the initial planning, consideration of new safety, reliability, and in some cases, enabling performance approaches for viability. For example, due to their huge numbers, if current accident rates prevail, UAS/ODM/PAV aircraft could crash at an unacceptable rate, causing life and property damage. Also, if humans in commercial space activities have serious health issues and/or there are unacceptable rocket viability issues/crash rates, these new, major markets (order of \$1T/yr.) could be rapidly curtailed until agreeable and effective changes are instituted, producing additional expense, delay, and reduced revenue. This report addresses such safety and reliability issues and includes: performance enhancement possibilities such as an enabling Air Traffic Control System (ATC), crash proof vehicles, increased range for aero, space debris removal, and human health for space.

Introduction

The major aerospace metrics are cost, safety/reliability, and performance. 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.

There are two emerging, and potentially massive, aerospace markets that were initiated largely based upon developing cost enablers/drivers and both of these appear to require greatly enhanced reliability/safety and performance enhancements/enablers. The first of these markets is the development and application of UAS/ODM/PAV, which is rapidly evolving. The second is commercial deep space, which is enabled by advancing technologies and space access cost reductions provided by reusable rockets.

UAS/ODM/PAV involve small, mainly vertical take-off and landing (VTOL), increasingly autonomous electric aircraft for a plethora of national security, service, commercial, and personal applications (Ref. 1). A major requirement for safety and reliability includes greatly decreased crash/hull loss rates as compared to extant commercial aircraft, which are already inordinately safe. This keeps the number of crashes low enough to be acceptable with the projected orders of magnitude more aircraft in the air. There are some 39,000 aircraft now and estimates for future UAS/ODM/PAV numbers are in the tens of millions or greater. The ultimate market is a fly/drive replacement for the automobile. The worldwide market for this new aero industry segment is projected to reach the order of one trillion dollars per year going forward. Additional requirements for UAS/ODM/PAV safety include: an air traffic control (ATC) system capable of handling millions versus thousands of aircraft, and operational/safety certification. Performance metrics include longer range for a given battery energy density.

All aspects of this emerging market are being invented and developed in real time. There are a hundred plus vehicle designs being researched by tens of companies. This ongoing UAS R&D is rapid, very competitive, explores technologies with new capabilities, and has application trade spaces with cost as a major metric. As such, it is termed by some as the "wild west" of aeronautics. Thus far the safety considerations mentioned above are not as well developed as will probably be necessary. The overall crash rate requirement is made more worrisome by the

fact that these air vehicles will spend much of their time over populated areas, versus commercial aircraft that fly over sparsely populated and water covered regions much of the time. For a given crash, there is therefore a greater chance of property and personal damage. However, there is usually less total overall impact per incident due to the smaller size of these vehicles, depending on what they impact.

For performance with electric propulsion, what is desired is range equivalent to that using heavy transportation chemical fuels. The market size for these vehicles is often proportional to achievable range. The term range is used either directly or to service multiple stops before having to recharge the vehicle. Range is a function of vehicle drag and weight for a given propulsion system. Additional performance metrics for these vehicles include acoustics and VTOL capability.

Another emerging aerospace market that requires improved reliability, safety, and performance for viability is commercial deep space, commercial space beyond geosynchronous orbit (GEO) (Ref. 2). Current commercial space is a successful and major business area that operates at GEO and below. This largely includes positional Earth utilities such as telecom, internet, navigation, weather forecasting, imagery, resource monitoring. Commercial deep space is nascent but investment and interest is growing rapidly. This is bolstered by the recent NASA shift to the moon before Mars, the discovery of water on the moon, and tech developments enabling cost reductions. Much of the current deep space commercial attention is focused on mining the moon, asteroids, and Mars for water, minerals, etc. The increasing capability of autonomous robotics and artificial intelligence (AI) enables a cost picture for such mining that is far more favorable than if humans were involved on-site in space. Estimates for human space presence are usually a factor of 500 or greater cost. There are not only increased costs associated with placing humans on-site, but also serious health and safety/reliability issues associated with the space environment (e.g. galactic cosmic rays (GCR), micro g or partial g, psychological challenges, equipage reliability, vacuum pressure, extreme temperatures, etc.) (Ref. 3).

The use of reusable rockets, systems, and equipage will greatly reduce overall costs and thereby increase business possibilities in deep space. However, the historical rocket loss rate of 1% or greater, i.e. on the order of one or more every 100 launches, robust over many decades now, may not be suitable for commercial activities, especially those with humans on board.

With an increasing number of satellites in Earth's orbit and thousands planned to launch in the near future, increased space debris is another safety issue that requires attention for viable deep space commercial activities (Ref. 4). Also, space tourism is a business activity that could be viable in deep space so long as the safety of space access and the health issues previously mentioned, are addressed.

Aerospace is experiencing a renaissance. It is booming and expanding in both the air and space domains into new commercial areas. These new areas require consideration of stringent safety, reliability, and performance issues for viability. If too many UAS/ODM/PAV aircraft crash and cause life and property damage, if humans during commercial space activities have adverse health effects or mortal impacts, or if rocket loss rates are unacceptable, than these new emerging markets could be curtailed until agreeable changes are instituted. This would result in additional expenses, delays, and reduced revenue.

The present report addresses these issues going forward, including selected performance enhancement possibilities. The projected requisite improvements in safety and reliability for UAS/ODM/PAV could be up to a factor of 1,000 to account for a 1,000 times more of them in the nation's airspace projected going forward (millions versus thousands). It is expected that the number of launches for reusable rockets in commercial space will increase because the cost associated with these launches will be reduced. However, a similar factor of 1,000 times improvement in launch reliability would be necessary to achieve the same safety and reliability as commercial aircraft on a per take off basis. Improvements of this magnitude, even factors of 10 to 100, will require changes to current practices, including addressing accident causes at the system of systems level.

The top reliability issues discussed in the next section include: human factors/errors, mechanical/equipment functionality, software/cyber threats, and environmental effects. The fundamental requirement for large improvements in safety and reliability is to accurately identify a range of inputs, including operational conditions over time, the equipment capabilities/functionality over time, the system of systems interactions, and whether or not these could lead to failure/loss of mission/overall functionality. This requires enlightened ideation of the potential risks. Of particular concern are the emergent properties of complex systems and their risk impacts. Overall, the current state of safety and reliability for the buildout of UAS/ODM/PAV and reusable rockets/resultant commercial space developments appear to be less than desired, possibly requiring orders of magnitude improvement. Safety is an emergent property of a system and complexity-based approaches are needed.

Current Causes of Serious Safety and Reliability Issues for Aeronautics and Space

Causes of aircraft accidents/crashes: (Refs. 5)

- 50% Pilot (human) error
- 23% Equipment failure
- 10% Environment/weather
- 7 to 10% Sabotage, terrorism, etc.
- 7% Other human error

Causes of UAS and drone crashes: (Refs. 6-8)

- 64% Equipment failure (e.g. controls, power/propulsion, communications)
- 32% Human factors

Causes of rocket failures: (Ref. 9)

- Engines/propulsion
- Guidance and control
- Human error
- Software
- Stage separation
- Equipment (e.g. pumps, wiring, valves, aged parts, sensors, etc.)
- System cascading failures
- Design
- Component overheating

Sampling of safety and reliability related issues in aerospace: (Refs. 10-14)

- Human error, major source of safety problems, crashes, even after many decades of R&D and technologies to reduce such (including controlled flight into terrain (CFIT))

- Equipment failures, due to design, installation, operational employment, maintenance, aging, environmental effects, and tipping points for cascading system failures
- Electron/photon related failures including cyber/software issues, EMP/space weather/radiation, jamming, failure of equipment essential for navigation, controls, sensing, propulsion, and communications, etc.
- Inadequate margins, especially with regard to a cascading system of systems failures where reduced capability does not fail the parent part but adversely impacts in serious ways the functionalities/piece parts that the overall system depends on for robust performance.
- Operation in extreme environments/in the presence of discrete extreme environmental/operational conditions (e.g. hurricanes/typhoons, bird strikes, extreme icing/rain/ dust)
- Air Traffic Control (ATC) functionality, possibilities of collisions, reduced system capacity, as the current ATC system is largely human operated – human factors.
- Bio becoming more virulent in space, (e.g. pathogenesis, corrosives). The human gut contains many microbes.
- Potential impacts of reusability upon safety and reliability and certification for such
- Human health issues (e.g. micro g, radiation, psychological, accidents, illness, etc.)
- Collisions/impacts with debris, birds, other vehicles, and the ground
- Wake vortex hazard, causing forces which cannot be controlled
- Fuel starvation (due to human factors), lack of sufficient fuel
- Costs/profits/schedule exigencies, “corner cutting”
- Oxidative chemistry, causing equipment failure
- Lightning and electrostatics, causing electronic failures, fires and explosions
- Planetary and moon dust, abrasive, corrosive, oxidative
- Fatigue and fracture, a prime design metric for much of aerospace equipage
- Weather, storms, wind, space weather
- Unknown unknowns, it is usually not possible to anticipate all combinational situations, conditions which will result in a reliability issue, we can become surprised reliability-wise
- Inadequate analysis and testing, due usually to either cost or inadequate knowledge or study reliability writ large can be compromised
- “Hazards”, hazards are major drivers for reliability design and engineering. As complete a set of especially combinational hazards is required.

Reliability and Safety Precepts/ hazards Approaches

As noted, aerospace reliability and safety subsume a particularly broad arena including: operational, system of systems/cascading system failures, design (e.g. mechanical, electronic, cyber, sensor, communications, materials, controls), rare events, human errors, weather (including space weather), impacts/collisions (including with birds), costs, fatigue/fracture, health issues (e.g. radiation, micro g, dust), testing efficacy, etc. (Refs.15-19).

Considering UAS/ODM systems and vehicles, thus far 64% of the increasing number of crashes are due to equipment failures such as propulsion/power, flight control, and communications. The rest are cited as human error and miscellaneous. This is quite different from extant commercial aviation, which has a sterling safety record and where only 23% of crashes are due to equipment failures versus equipment failure as the dominant cause for UAS/ODM. This difference strongly and obviously indicates the need for much better design and certification for UAS/ODM, which is thus far a class of vehicles and an overall business based upon inexpensive equipment. Market viability will likely dictate serious reductions in crash rates to account for the increase in the number of flying vehicles. As this field moves forward, improved equipment and addressing the risk of human factors is needed to increase safety and reliability.

The inability over many decades to materially improve the accident rate of rocket launches is likely related to acceptable insurance rates and the historically high cost of space access and the lack of fiscally acceptable margins to work serious reliability improvements. The advent of reusable rockets and resulting inexpensive space will, among other major changes, enable more cost effective safety and reliability.

A sampling of the components, arenas, and approaches for reliability/safety in aerospace that have been found or suggested to be useful include: (e.g. Refs.20-29)

- Redundancy, backup systems , utilized on human rated systems especially
- Certification, regulatory (IAF, American Society for Testing and Materials (ASTM) standards)
- Inspection, including NDE, to identify emerging problems early for remediation
- Integrated vehicle health management (IVHM), utilization of the increasing capability of sensors, actuators, computers and AI to identify safety issues early and enable corrections
- Positive margins-to-fail-safe in the limit design approach, to build in “margins”, for inaccuracies in specification of design parameters and design details.
- Digital twin, where the in service impacts on equipment are computed and compared with onboard sensors in real time for identification of emerging issues.
- Manufacturing/installation care (level of workmanship including requisite training)
- Repairability-to-self repair, related to larger margins.
- Recovery approaches (e.g. Safe to Ditch, chutes, and morphing)
- Emergency systems, including those that ensure human survivability
- Electric propulsion to obviate fuel fires
- Reliability analysis including probabilistic methodologies informed by applicable big data/sensorization, uncertainty quantification
- Preventive maintenance, a first order approach, guided by inspections, digital twin
- Obviate single points of failure, as a design approach
- Detailed operational mod sim, systems level, all disciplines, as an evolving alternative to physical testing
- Resiliency/graceful degradation, fault tolerant systems
- Commonality, for parts exchange, may enable reduced testing requirements
- Reliability and safety a major design metric, along with the usual weight, cost, functionality major design issues.
- Collision avoidance, the ever increasing sensor and computing capabilities is enabling major improvements in this.
- Preflight checks, increasingly such checks will be accomplished by sensors/ robotics and AI.
- Configuration management, as a major aid to ensure overall design and operational integrity.
- Sources, nature of, checks for, and minimization of human error, since human error is a major source of safety/ issues/ accidents this is critical, and has proven to be very difficult.
- Ability to override autonomous robotics systems, we are not yet at the technical state termed “trusted autonomy”, robotics and AI are designed largely by humans, and therefore human error possibilities exist.
- Simplicity, lower part count (including via printing manufacturing) this has proven to be an effective safety approach, less parts , functions to fail

- Testing at all complexity levels from piece parts to system of systems, given the developing status of computation and knowledge of initial conditions in detail it is still important to conduct physical testing including at the operational, systems level.
- Requirements specification and their validation, involves checking design assumptions and adequacy and predictions of operability, service life.
- Materials and morphing materials/structure, ensuring that the materials utilized are the ones specified, are per the design. Morphing materials and some multifunctional materials are at an early stage of development, require detailed scrutiny
- Zero defects manufacturing, a goal which is useful to increase overall safety awareness and care
- Condition documentation, materials processing, construction, and in-service activities alter the condition of everything from materials to systems of systems, inspection, computation and associated documentation is a requirement for decisions regarding potential safety issues, reliability and remaining service life/ requisite repairs.
- Flow control for weather proofing, there are many ways to control-to-obviate flow separation, the cause of many in atmosphere aerospace accidents, including flow separation associated with wind gusts and heavy precipitation and icing.
- Operational impacts forecasting, projecting the various loads and conditions, including combinationally, a device will be subjected to operationally.
- Crash proofing, “flying while hurt, identify safe local landing areas and land versus crash
- Continual study of previous reliability, safety experiences, issues, instantiations, crashes, knowledgeability, National Transportation Safety Board (NTSB) data bases, NASA lessons learned, and the nuclear weapons stockpile stewardship efforts
- Cost reductions to afford greater safety/reliability, The usual major metrics are Cost and functionality, it is often possible, if cost is reduced, to employ the savings, or a portion thereof, to improve safety. For human spaceflight, the major metrics are Cost and Safety. We are busily reducing cost via reusable rockets and ISRU , and thereby enabling safety improvements with respect to radiation, microg, reliability etc.

The foremost approaches to reduce major causes of accidents includes Autonomy to largely obviate human factor issues. This can incite its own set of concerns which will have to be identified and addressed. Compared to human operations, the potential benefits of autonomous machines are many:

- Exclusion of human operator error. For example, while machine errors exist in self-driving cars, they are fewer than those committed by humans.
- Autonomous machines are more durable and patient with far longer duty cycles not limited by human attention spans and need for sleep, nutrition, etc.
- Potential for greater efficiency and speed
- Possibilities for size reductions. Working spaces don't have to be sized for humans and the conditions required to keep them healthy.
- Increased knowledge. For example, IBM's Watson super computer uses deep learning, which has proven successful in medicine because the machine knows far more than individual practitioners.
- Reduced cost. Once operating and until repair is needed, most system costs involve paying people. The machines are famously taking the jobs. As a nascent example, self-driving trucks are being developed and are expected to replace jobs previously occupied by truck drivers, which is a substantial employment segment.
- New functionalities beyond those available from human capabilities. Due to superior sensor suites, machines can operate under conditions such as high radiation levels where humans cannot go safely.

Additionally a major approach is to include sensors/instrumentation/artificial intelligence (AI)/on and off board, for all physical scales, to discover and monitor issues as they arise. To inform AI with regard to the need for corrective actions, requires machine ideation to intuit the presence and nature of unknown unknowns with regard to vehicle safety and reliability. Also, due to an absolute requirement for electronics for operations writ large including communications, and navigation/ controls, need electron/photon protection and functionality, protection from cyber-attacks, electromagnetic pulse (EMP), and jamming.

The current safety/reliability engineering practice includes the following set of tools/ approaches:

- Hazard analysis
- Fault tree analysis
- Failure and damage modes and effects
- Probabilistic risk assessment
- Human error analysis
- Simulation modeling
- Experimentation
- Root cause analysis
- Degradation/life units
- Plus: Lessons from history, expert opinions, best practices, ideation (especially for unknown unknowns and at the systems of systems levels), foresight, and vetting of new technological approaches in a system of systems context

The rapidly developing UAS/ODM industry does not yet appear to heavily emphasize reliability and safety. Particular space-related concerns are rocket performance/reliability and the health concerns and related cost and schedule impacts associated with sending humans into space. These two frontier revolutionary and potentially very large industries are, as most nascent industries are, sensitive to costs across the board. Consideration of safety/reliability issues early on in the design cycle including at the systems level is perhaps a cogent approach to control costs associated with safety and reliability and ensure viability.

Enabling UAS/ODM

(Ref. 1 and Refs. therein)

Unmanned Air Systems (UAS)/On Demand Mobility (ODM) Issues

The nearly concomitant development of IT capabilities such as navigation, computing, automatics-to-autonomy, ubiquitous sensors, and now electric propulsion and additive manufacturing, has spawned a rapidly growing market in electric aircraft drones and UAS for many applications and functionalities. These include: recreational, delivery, auto replacement, public services (e.g. fire, law enforcement, weather, mapping, search and rescue, inspection, disaster relief, and first responder), agriculture, national security, construction, and media and research. This in turn has instigated the rapidly developing efforts for what has been termed On Demand Mobility (ODM), including Urban Air Mobility (UAM). On Demand Mobility is initially piloted, but will eventually become autonomous UAS carrying human passengers.

The metrics for these markets include:

- Acquisition and operation costs
- Safety and Reliability
- Ease of use
- Acoustics
- Close proximity operations

- Ride quality
- Emissions
- Range and efficiency
- Certification
- All-weather operation to the extent possible or feasible
- Crashproof

These are in addition to the enabling autonomous operational and ATC systems to provide airspace access for the projected many millions of vehicles.

The current ODM and UAM efforts are investigating VTOL with electric propulsion, distributed propulsion, and flow control as enablers. The literature is rife with large numbers of non helo VTOL devices and approaches with several-to-many lift fans. Typical benefits include: lower noise, drag, vibration, cost, maintenance, and safety. As the costs of renewables for electrical generation continue to drop and the batteries continue to improve, it is increasingly feasible to unload the lift fans for improved acoustics. What has not yet been seriously considered for ODM/UAM or personal air vehicle (PAV), for VTOL operation is a stacked, stopped rotor for efficient cruise. For super short take-off and landing (STOL) operations there is the channel wing with circulation control, and for lower cruise speed STOL various flavors of autogyro.

Electric propulsion eliminates engine exhaust noise, enables distributed propulsion and flow control, and lighter engines, along with more of the many benefits of electrics.

The Prospective Advantages of electric propulsion:

- Regenerative energy recovery during descent and landing, analogous to regenerative automobile braking
- Battery heat production, could be utilized for cabin heating, deicing, or regeneration
- Higher altitude operation feasible, electric Propulsion system not as sensitive to lower pressures
- Reduced cooling drag, lower heat losses than gas turbine propulsion
- Quieter, obviates exhaust noise
- Reduced vibration, better ride quality
- Fewer inspections, electric motors have far fewer parts and those parts have a very long life.
- No engine flameouts or restarts, but could have battery operational issues.
- No fuel explosions during crashes, although battery fires are possible
- Power train efficiency greater than 90%, nominally twice or greater than Internal combustion and gas turbine engine chemically fueled propulsion
- Much lower energy costs, the electric energy to charge the batteries is lower cost than aviation fuel
- High reliability, per the operational history of electric motors
- High efficiency over most of the power envelope
- Up to six times motor power to weight, compared to combustion engines
- Reduced maintenance, due to higher electric motor reliability and lower part count/ design
- Far fewer parts
- Less expensive
- Higher torque
- No vehicle emissions
- Distributed, scalable propulsion, can position small electric motors for distributed propulsion, flow control, vehicle control, drag due to lift reduction

As stated, among the metrics for UAS/ODM etc. are reliability/safety and performance/costs. The expected increase in the number of these air vehicles going forward (three orders of magnitude greater), when applied to the current highly regulated and certified/developed commercial aircraft crash statistics strongly suggests a large-to-unacceptable number of crashes. Therefore, means should be ideated and developed to greatly improve an already extremely low commercial crash rate for application to UAS/ODM operations. The best case scenario would be to strive to make UAS/PAV vehicles crash proof. One approach to improve the cost/performance metrics for this class of air vehicle is to develop successful stopped rotor approaches which utilize the VTOL enabling rotor as the lifting wing for cruise in a stopped mode (Refs. 30).

Toward Crash Proof UAS/ODM

There are many occurrences which could cause a UAS/PAV crash. The current most prevalent cause of crashes with these devices are due to equipment failures (65% of crashes). This cause should be largely fixable with careful design/construction, operational care, and certification. The primary market issue for these air vehicles is cost minimization, and therefore cost increases associated with improving safety and reliability can be problematical.

A second crash-producing issue is human errors of various types. This is the dominant cause of crashes for commercial aircraft. The increasing utilization of autonomy should reduce this cause of crashes. There is a plethora of other causes that lead to crashes including weather and collisions mid-air with the plane (e.g., birds).

There are three obvious ways forward to foster crash proof behavior/capabilities:

- Design/deploy iron birds: vehicles developed with the design precept of obviating the various experiential causes of crashes
- Fly while hurt or keep flying. Not possible for all potential damage, issues, but is a design option which could incorporate self-healing aspects/materials/morphing and the associated AI.
- Gently land in a local area that would minimize damage both on the ground and to the vehicle. This is perhaps the best approach which would incorporate piece parts of the other two approaches. This would involve: detection/selection on the fly of a suitable local landing site, means of flying/gliding to that site, and the means to land safely.

Landing site selection for UAS, where flight is commonly over developed/populated areas, is not straightforward. Flattish rooftops with suitable structural strength are an obvious possibility, especially in cities. Otherwise, parking lots, low traffic roads, or open spaces/yards are possibilities. Obtaining the requisite data regarding such local possibilities can be via on board sensors or accessing what is evolving as a large swarm of low Earth orbit (LEO) Electro-optic satellites with the capability to stare anywhere 24/7/365 providing real time data on the local landscape. This is an evolving capability of the ongoing IT and AI revolutions.

Flying or gliding to the selected emergency landing site could be facilitated by on board/deployable/flyable chutes or other means to provide vehicle control and lift. Inflatable auxiliary wings are also an option, as are autorotation blades. NASA currently has efforts with regard to landing safely locally termed safe-to-ditch and learn-to-fly. An obvious alternative or adjunctive approach is utilization of energy adsorptive vehicle designs and materials to both minimize damage to the vehicle and what it impacts.

This mélange of safety, reliability, certification, crash proof, regulatory issues, maintenance, inspection, and design precepts is required to ensure viability of the evolving, eventually some

\$1 T/elo new UAS/PAV aero markets. This is necessitated by their increasing numbers and where they fly and is a key issue regarding societal adoption. There are several additional arenas of operational concern including: acoustics, flight in urban canyons where vortical atmospheric wind and vehicle induced flows can occur, and of course a viable ATC system for many millions versus many thousands.

UAS/ODM Requisite/Enabling ATC System

The current limited capacity (thousands of aircraft) ATC system can be non-linear, i.e. smallish changes, occurrences producing large problems, issues has to 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 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 the communications, navigation, software, sensors, collision avoidance, architectures, and AI. All the piece parts and their system of systems which 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 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 include many orders of magnitude greater numbers of air vehicles and substantial reductions in latency.

UAS /ODM Performance Enhancement Approach

(Ref. 1 and Refs. therein)

The major design metrics for UAS/ODM/PAV include: acoustics, emissions, reliability/safety, and sufficient range and efficiency with overall costs sufficiently low enough to engender a profit. Batteries and the renewable energy to charge them are evolving to where electric propulsion is feasible for increasing ranges, thereby seriously addressing emissions. In turn, electric propulsion proffers scalable distributed VTOL propulsion with numerous rotors/lift fans that address noise.

In terms of design, concomitant with reliability/safety is range and efficiency. A lower weight/lower drag/efficient airframe reduces the requisite battery capability and increases range for a given battery SOA. There is a plethora of approaches to reduce weight and drag on airframes, both individual technologies and synergistically. Among these approaches is one that is particularly interesting: the stopped rotor.

The stopped rotor approach utilizes a low noise, lightly loaded tip driven rotor (no tail rotor needed) to provide VTOL which, once in the air, is stopped and the rotor becomes the wing for cruising. The improved performance of this approach was recognized early on and has been worked since the 1950's with two sizable efforts. The first was the X-wing in the 80's, which used circulation control and never flew. The second was the Canard Rotor Wing program in the

early 2000's, which after two crashes, was stopped. More recently the Navy and the Australians have been pursuing versions of the CRW approach. The major issue with the stopped rotor approach occurs when the rotor is stopped, which is the transition period. At that point one of the blades is facing the wrong way. Various solution spaces to address this issue have been tried. Two such approaches that appear to work are rapidly rotating the errant blade 180 degrees and circulation control. As the blade stops, lift forces dynamically shift and the cruise propulsion system kicks in, creating worrisome aircraft stability and control issues.

Some suggested ways forward that may be of interest to actualize the stopped rotor VTOL UAS approach include the following:

- Utilize electric tip drives on the blade which obviates the need for tail rotors and reduces the blade drag due to lift. These can contribute to propulsion during cruise.
- Thrust vectoring, AI, morphing surfaces, etc. for stability and control.
- 180-degree rotation of the errant blade or morphing leading/trailing edge regions to alter the blade contour during rotor stoppage. One approach for morphing surfaces is using thin blades that project backward at the desired trailing edge to stretch a tailored elastic airfoil covering. This forms a suitable trailing edge region contour that retracts into the airfoil in the desired leading edge region. Inflation and contour tailoring of these elastic coverings might be efficacious.
- Strut-braced blades for greater span, lower drag due to lift, and to support the tip drives.

UAS/PAV approaches to reduce weight and drag, reducing the requisite battery energy density, and increasing range include:

- Flow control or designer fluid mechanics - Designer fluid mechanics subsumes a large number of flow control approaches and applications. These include: laminar flow control (LFC), mixing enhancement, and separated flow control for high lift, vortex control, turbulence control, and favorable wave interference for drag reduction. With the advent of the issue of battery weight for electric vehicles, LFC is especially under active consideration to reduce the requisite battery capacity. For turbulent drag reduction, the options include relaminarization and riblets. Electric propulsion proffers the possibility of straightforward distributed energy for flow separation control.
- Aero/propulsion synergies – Conventional design practice in civilian aeronautics is to essentially separate the aerodynamics and the propulsion systems. Examples of aero-propulsive synergies include:
 - Circulation control wings up to a factor of four increase in C_L (Lift Coefficient)
 - Boundary layer inlet: Ingesting lower momentum air for up to 10% to 15% propulsion efficiency increase.
 - Wing tip engines: To reduce drag due to lift. Wing strut and truss bracing are conducive to wing tip engine placement.
 - Thrust vectoring: Placing the engines at the rear of the fuselage and utilizing them for aero controls in lieu of the weight and drag of the empennage.
 - Hybrid laminar flow with leading edge suction utilized for high lift separation control.
- Wave drag reduction - Approaches include: Wing sweep, area ruling and reduced thickness, as well as wing twist, camber, and warp. Non-linear techniques include: Nose spikes, either physical or via forward projection of energy, gases, liquids, or particulates to extend effective body length. There is another class of approaches which utilize favorable shock interference. They utilize shock waves via reflection or interaction to create a favorable interference for body thrust, lift, or both. Parasol wings can provide on the order of a 20% improvement in overall lift-to-drag ratio at cruise.
- Drag due to lift reduction - Elliptical loading, increased aspect ratio and span, lower lift coefficient, and reduced weight are the primary approaches. This has been addressed in many cases via creative overall aircraft configuration design (e.g. truss braced wings). The

use of non-planar lifting surfaces such as distributing the lift vertically through various approaches including upswept tips and multiple, vertically spaced wings, can provide sizable reductions. Also, devices can be inserted into the tip flow to produce or recover thrust and/or energy from local flow angularity. These include tip turbines for energy extraction, winglets, vortex diffuser vanes, tip sails, and other tip devices such as wing grids, spheroids, and c-tips. Eliminating the physical wing tips can be accomplished either using ring wings or joined wings and tails. The truss-braced wing, as currently conceived, reduces DDL 75% by the simple expedience of doubling the span. This is enabled by the structural characteristics of the external truss, creating a new set of optimization parameters and approaches.

- Landing gear weight reduction – Landing gear is 33% the weight of long-haul transport fuselages and 63% the weight of SST fuselages. Therefore, they constitute a target rich environment for vehicle weight reduction. Typically, gear includes large, heavy brakes for refused takeoff. Drag parachutes can be employed to handle refused takeoff, accruing sizable weight reductions. The structure of the gear itself is typically sized for high impact landings. Such loadings could probably be minimized in frequency and impact strength via autonomous operations, adjusting the lift system to the ground proximity and descent rate.
- Revolutionary materials and structures - There are several extant, but low technology readiness level (TRL), approaches to significantly reducing the dry weight of aircraft via revolutionary materials and structures. By printing at the nano scale, technology is developing to produce superb material microstructure with far fewer dislocations and grain boundary problems. This greatly improves material performance. Another approach for ultra-performance materials is to attempt to merge nanotubes into a contiguous structural material. There are several approaches with estimates of performance improvements in the 3X to 8X range. There are also continuing efforts, with respect to composites, claiming 10X the performance of aluminum. Revolutionary structures approaches include externally truss-braced wings (Refs. 89, 90).

Enabling Commercial Deep Space

(Ref. 2 and Refs. therein)

There are a myriad of reasons for humans to go into or operate in space:

- Hedge the bets of the human species with regard to serious asteroid impact (e.g. becoming a multi-planet species), Colonization
- Positional Earth utilities, a long-standing and thriving commercial space industry, GEO and below
- National security
- Science
- Deep space commercialization
- Space based resources

Projections for commercial space include some 10,000 companies, 27,000 satellites and expansion beyond GEO (inner space) into outer space/deep space, with an overall evaluation of over \$1T/yr. by 2040.

There are two distinct commercial space activities: commercialization of government activities and where the customer is another commercial or private entity. Thus far the preponderance of commercial space activities has been near space, GEO and below positional Earth utilities, with increasing activity in commercialization of government functions. What has largely been missing is beyond GEO, outer/deep space, real commercial business. As a result of the technologies and approaches discussed herein, this activity is on a growth curve, initially involving space resource acquisition/utilization and moving toward colonization of places such as moon(s),

Mars, and eventually more exotic places such as the poles of Mercury, the upper atmosphere of Venus, and Titan.

Some of the basic precepts of much of this increase in outer space commercialization include: reusability, in situ resource utilization (ISRU), resiliency, cost/return on investment (ROI), competition, and leveraging. The myriad extant space resources include: CO₂ (e.g. on Mars), water (e.g. on the moon, Mars, and asteroids), minerals, solar energy, volatiles, microgravity, space, vacuum, and low temperature. The option spaces include: reusable or expendable, robotic and/or humans, solar/chemical/nuclear/positron power generation and resupply or ISRU.

Commercial Space Planning/Possibilities

- Major LEO constellations of small sats for high speed internet and electro-optics, expanding the number of satellites from the order of 1600 now to some 20,000 plus in 10 years. The electro-optic sats could enable staring anywhere 24/7/365.
- Utilities for beyond GEO to service both public and private customers, including communications, energy/fuel, transportation, maintenance/repair, life support, etc.
- Mining: Moon, Mars, and asteroids for anything commercially viable such as water, minerals, Helium-3, rare earths, volatiles, mass, etc. There are purportedly 1800 sizable near-Earth asteroids at lunar distances from Earth or less.
- Entertainment including: virtual reality (VR), videos, and virtual presence to enable spending an evening exploring Mars from your living room
- Collect anti-protons which are trapped in the Earth's magnetosphere. Anti-protons are exceedingly expensive. In terms of energetics, they're some 9 orders of magnitude greater than chemical due to 100% mass to energy conversion.
- Asteroid defense, detection, and tracking, diversion of those deemed capable of causing grievous harm
- Space solar power for planets, moons, and asteroids, in space, delivered via energy beaming (e.g. MW or lasers)
- Space beach combing, the identification, collection, destruction, repurposing, and remanufacturing of space debris. Of particular interest is boosting the International Space Station (ISS) into a parking orbit and scavenging it for piece parts
- Trash dump, putting trash in parking orbits for safe storage. This includes components of nuclear waste if it's certified launch indestructible
- Space manufacturing in orbit, in space, on other bodies, or enroute. Products identified thus far with major improvements when manufactured in micro g include: pharma, fiber optics, ball bearings, light-emitting diode (LEDs), solar panels, organs, hearts, protein crystals, in addition to fuels, on planet/body human commercial space equipage, or anything that makes economic sense
- Space hospitals if micro g or other in-space conditions prove to be efficacious for specific human ills
- Space tourism/colonization of moon(s), Mars, Titan, poles of Mercury, upper atmosphere of Venus, and asteroids in space
- Quantum technologies and quantum computing that utilize the quiet conditions in space including vacuum and low temperature to delay de-coherence, and stabilize quantum states
- Positional Earth utilities, telecom, internet, navigation, weather, imagery/E-O, resource monitoring, etc.
- Space weather forecasting. This has become increasingly important due to its impacts upon satellite operations as satellites proliferate and society relies more upon their functionality.

Commercial Deep Space Issues

There are many serious reliability, safety, and performance issues for commercial deep space. These include the reliability of rockets vs. commercial aircraft that are orders of magnitude more reliable. This is particularly critical for space tourism and humans in space. Thus far the human space mortality issues have been connected with equipment and operational shortfalls. In addition to this are the space presence impacts upon human health including studies that show that biologics in space can become more virulent. Humans can carry 1000 plus biologics in their intestines, begging the question of whether these benign biologics could morph into serious corrosives or pathogens over time in space.

There are also issues with space dust. Moon and Mars dust are a health and operational problem for on-planet/moon activities. Controlling dust is a first order issue which needs to be researched and mitigation approaches designed into the mission. Dust on Mars is abrasive, electrostatic, magnetic, oxidative, and chemically reactive. It contains silicates, gypsum, arsenic, cadmium, and beryllium, as well as perchlorates, which affect the thyroid. There is concern that the dust could become much more corrosive, a greater problem once inside habitats at their higher pressure, temperature, water and oxygen content. Then there is space debris, becoming ever more serious an issue, with thus far no cogent extant solution spaces.

An additional major concern/ current shortfall for commercial deep space is cost/ROI/profit.

Human Health Issues in Space (Ref. 3 and Refs. therein)

The following is a worrisome and incomplete list of human health issues and concerns for humans in space: The basic differences in health-related parameters between the ISS in LEO and the missions to and from the moon and Mars include a longer time frame. For example, currently it takes 3-years roundtrip using expendable rockets versus the six months tour on ISS. Spacecraft are also exposed to microgravity and full galactic cosmic ray (GCR) versus only 45% on ISS due to the effects on radiation of the Earth's magnetic field. Attendant increased time-related reliability, safety, psychological issues and other health concerns also increase for missions to and from the moon and Mars. The detailed nature of the potential clinical health impacts for humans at Mars and their potential synergistic effects are largely unknown. Where the impacts are known, the effects appear to scale in severity with the exposed time in space. The potential effects of the .38g on Mars or the 1/6th g on the moon are also unknown, but partial gravity is expected to relax the issues experienced on ISS during microgravity. The many and various mitigation approaches employed thus far are mainly directed at trying to establish conditions closer to those on Earth, conditions which resulted in current human physiology.

Identified Unmitigated Human Health Issues in Space

- Mars dust contains perchlorates about 10,000 times higher than Earth levels. They are small, sharp, and highly oxidative particles known to impact the thyroid and respiratory and cardio-pulmonary systems.
- Pathogens, or in-space biologics, that have been observed to become more virulent in combination with immune system degradation. Other immune systems impacts are expected from weakened t-cell function and immune system weakness due to the combination of radiation, microgravity, and psychological issues
- Microgravity allows fluid shifts that cause: eye/vision changes that blur vision upon abrupt movement; motion sickness that affects balance and appetite and causes dizziness and stuffiness; DNA damage such as double strand breaks, chromosome aberrations/mutations,

attenuated repair process; down regulation of P53; weakened t-cells; 1% per month bone mineral loss (especially calcium) and early onset osteoporosis and kidney stone propensity; muscle atrophy up to 20% loss in 5-11 days; skin irritation; cardio-vascular deconditioning; cardio arrhythmia; and heart degeneration including 30% to 50% decrease in maximal O₂ uptake due to blood cell and capillary altered interactions and blood volume loss; orthostatic hypotension and low blood pressure; neurologic, brain, cerebrovascular, and neurovestibular changes as well as reduced release of neuro-transmitters; effects on spinal fluid; sensory changes and dysfunction; increased homocysteine; liver damage including long term scarring and non-alcoholic fatty liver disease; and finally fibrosis

- Space radiation present both in space and on planet/body causes: radiation sickness, degenerative tissue effects, DNA damage, DNA repair process alterations, and oxidative DNA damage, as well as immune system degradation. This includes: significant reduced ability to produce blood cells, anemia, carcinogenesis including leukemia, tissue degeneration, respiratory effects, cataracts, heart, cardiovascular, and digestive system impacts, as well as neurologic effects, central nervous system and cognitive impairment, Alzheimer's (white matter hyperintensities of the brain) reduced length and area of dendrites, performance decrements and memory deficits, loss of awareness, focus, and cognition. A recent study indicates that GCR causes collateral tissue damage to adjacent cells (called bystander cell damage from heavy nuclei) and could increase the cancer risk by some factor.
- Psychiatric effects due to a combination of physiological impacts already noted plus distance from Earth, diet changes, sleep deprivation, and close proximity to other crew members
- Toxic chemical exposure from spacecraft components
- Reliability/life support system failures, spacecraft propulsion, and other mechanical failures including sensors and human errors
- The usual space conditions of cold and vacuum which at conditions in space outside a habitat or a space suit are deadly
- Then there are the potential synergistic effects of all of these combined, which are at this point a work in progress. Thus far, only the Apollo crews have been subjected to micro g and full GCR, but for only a few days. As stated, these mostly tend to become more onerous with time in space, as recently evidenced by Scott Kelly's comments with respect to changes to his health as a result of his nearly one year in space on the ISS versus the usual 6 months tour in space.

Thus far, engineering system failures have been the major cause of human death in spaceflight. Another concern is radiation that causes a mutagen in a pathogen when the immune system is compromised and the medication on board does not work because the human metabolism has shifted. It is the potential interaction of factors that nobody has considered which puts human health in unknown danger while in space. Many of the risks associated with long duration space travel are not fully understood.

Mitigation Approaches for Human-Mars Health Issues

As stated above, NASA is developing and proving out a robust suite of micro-g countermeasures including exercise, which thus far mitigates many of these microgravity effects. Some experts have written that many to most of these microgravity effects are simply the body adapting to microgravity, are mostly reversible, and in the microgravity environment, such changes are not necessarily adverse. However, the widely held opinion is the less time spent in microgravity the better.

Here is a short list of mitigation approaches being considered for human-Mars health issues:

- Exercise places loads upon muscles and bones to counteract the microgravity effects mentioned above. This is proving to be increasingly efficacious per ISS experiences. While mitigating the musculature and skeletal issues, exercise also helps maintain the immune system and cardiovascular fitness. There are, however, some effects of microgravity that exercise may not be as effective in mitigating including impacts upon vision.
- Nutritional and dietary supplements plus pharmaceuticals, anti-oxidants, and similar regimens are also proving to be efficacious and are a work in progress. Biological countermeasure research is upbeat with respect to several substances, but this research is in its early days. Although it's still too early to determine implementation, there are long-term possibilities for the future of genomics and synthetic biology to solve catastrophic diseases and perhaps someday space harden humans.
- Conventional space radiation protection shielding using low molecular weight materials required for high atomic number (Z) radiation, requires a sizable to large amount of additional spacecraft weight and cost. Reduced LEO access costs, such as proffered by reusable rockets (up to a factor of 14 less cost to LEO), would be enabling. Materials and their arrangements as components of spacecraft architecture are a contributor to radiation protection, but additional measures are also required. Potential radiation protection approaches include: active approaches using magnetics and electrostatics including nano-forest electrostatic concepts to reduce the requisite gap voltages and magnetics moved farther away from the capsule/in-space habitats, and potentially mini-magnetosphere, and plasma. A reusable radiation protection overcoat that remains in orbit may be the better approach for minimizing MLEO and dose over time. Then there is the possibility of redirecting highly energetic particle radiation (GCR) using crystals as is common practice in accelerator science.
- Fast transits allow for much shorter round-trip durations to reduce human exposure time to space conditions that affect human health. NASA has a new nuclear battery approach study that proffers powering the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) and results in a 200-day round trip to Mars versus the usual roundtrip of 3 years. This shorter trip time could largely solve many of the health issues by increasing the relevance of 200-day ISS conditions while reducing the requisite MLEO [mass in low earth orbit] necessary for long-duration missions lasting 3 or more years. Fast transits are also likely to show reductions in cost just like that experienced by reusable rockets. Given "the continuing reductions in costs of space access fast transits may be affordable via chemical propulsion.
- Artificial gravity (AG), created by rotating portions of the in-space habitat, is thought to be more efficacious than exercise in resolving some health issues associated with microgravity. However, AG concepts pose additional requirements on the in-space architecture generally involving various rotational components.
- Space flight during solar maximum, during which time GCR levels are lower and therefore have reduced negative health impact
- Applying partial vacuum to lower body parts to pull fluid away from the head, eyes, and upper body. This mimics the effects of gravity upon body fluid distribution.
- Hypnosis to induce sleep for alleviating many issues related to sleeplessness
- Electrical stimulation and vibrating platforms for bones/muscles to induce additional circulation.
- Improved virtual and robotic on-spacecraft medical care including prevention, diagnosis, treatment, and surgery including robotic surgery.

Space Debris (Ref. 4 and Refs therein)

Since the late 1950s, we have launched around 6600 satellites, approximately 1130 of which are still operational. However, many of the non-operational satellites are still in space. There have

been approximately 240 explosions in space and many collisions, two of which were major events. All of this has contributed to the current space debris issue.

The amount of this space debris is daunting. Estimates indicate about 6000 tons, with some 5000 pieces greater than 1 meter in size, 22,000 greater than 10 cm, 700,000 greater than 1 cm, and 150,000,000 bits greater than 1 mm. 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. A quote from a 2011 National Research Council report entitled *Limiting Future Collision Risk to Spacecraft*, summarizes that year's outlook, which is becoming ever more serious: "When a handful of reasonable assumptions are used in NASA's models, scenarios are uncovered that conclude that the current orbital debris environment has already reached a 'tipping point,' meaning the amount of debris currently in orbit—in terms of the population of large debris objects, as well as overall mass of debris in orbit—has reached a threshold where it will continually collide with itself, further increasing the population of orbital debris."

The increase in orbital debris will lead to corresponding increases in spacecraft failures, which will only result in more debris in orbit. The increase thus far has been most rapid in LEO, with GEO potentially suffering the same fate, although over a much longer time period. The exact timing and pace of this exponential growth are uncertain, but the serious implications of such a scenario require careful attention because of the strategic and commercial importance of U.S. space operations. In the literature, this cascading of collisions producing ever more debris until the space region is essentially unusable is termed the Kessler Effect. Given the increasing worldwide reliance upon space assets, our positional Earth utilities have made space debris an increasingly serious problem.

Overall, current solution spaces include

- Detect/ track and avoid.
- Protect from impact [e.g. Whipple shields for small debris, install critical/sensitive portions in the interior of the spacecraft, or harden the design so it can take the hit]. This approach may not work for larger debris, or may be too expensive. Some external critical parts, such as solar panels and antennas, are obvious issues when considering protection under this latter solution.
- Self-remove: designing objects that deorbit at the end of their life, extend drag-producing devices, move to parking orbits, or utilize the higher drag during solar maximum.

Space Reliability/Safety Status and Prospective Ways Forward

(Refs. 33, 34)

The current status of space reliability and safety is typified by the loss rate of space access which include: accidents, crashes and explosions. Issues like these occur the order of once every 100 launches, a rate of 1% or greater. The launch of the Space Shuttles experienced a smaller number of flights between accidents, while space tourism and the commercial space business probably require a number far larger. The current state of affairs of space reliability and safety aspirations is the updated NASA NPR 8705.2c, which includes the human rating requirements for space systems. This sets forth the approaches and procedures for LOC [loss of crew] greater than 500 launches and descents, and greater than 270 for launch, descent, and in-space activities. The maximum g loading is three. Also included are rescue and emergency systems. The usual space structural design metric for margin is 20% above maximum loads. A major space access company is designing with 40% to enable reusability and human rating. They are also employing continual upgrades to improve reliability.

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. The 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 current committees sponsored by the IAF and ASTM to exchange information and develop safety/reliability standards, respectively, with regard to commercial space flight. As stated, there is evidently not yet an agreed upon 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.

Obvious major safety improvement opportunities include:

- Even greater structural factors of safety
- Reduced uncertainty writ large, from material characterization and operational conditions to systems of systems.
- Back-up, fail safe, and safe systems
- Extensive sensor suites and IVHM
- Emergency and recovery systems
- AI monitoring/solution generation and execution
- Systems of systems/operational aspects/potential hazards
- Tipping point identification

Potential Mission Analogs for Practical Approaches to Verification of Safety and Reliability

Ways forward and suggested approaches must be verified. Assumptions made in simulations and analysis must be validated. This means testing. But, how and where? NASA uses “in a relevant environment” and “mission operational environment” with respect to technology maturation (Technology Readiness Level). NASA adopts a verification philosophy of “Test Like You Fly” to guide experimental verification of system performance and revealing unforeseen failure modes (Refs.35, 36). All these point to the need for representative testing analogs for addressing the conditions expected in the intended mission uses.

As mentioned previously, the missions discussed herein are far more stressing with regard to safety and reliability than current missions. Commercial airline flight reliability numbers will not be sufficient for the expected UAS markets. Astronauts staying on the ISS do not fully represent the many other conditions of radiation and the combinations of long duration exposure to many health degrading environmental factors on the human body in deep space. The emergence of inexpensive space access should greatly increase space flight rates.

Test Like You Fly

History has demonstrated the limitations of mathematical formulas alone to yield sufficient designs. At times, overly confident and premature use of aerospace systems led to costly recognition of unknown unknowns, resulting in construction of new ground-based facilities eventually yielding far superior designs due to a more thorough understanding of vehicle behavior in relevant environments.

What is different today is that continued advancements in technologies allow for rapid prototyping, quicker understanding of cause and effects, and faster turnaround on next generation designs. Industry demonstrated the success of this process by offering launch vehicles at far less cost than

its competition due to efficiencies in the design that allowed for reusability. This development process can be applied to other aerospace systems such as those needed for the two aerospace revolutions mentioned herein.

What is not different is the human element within both aerospace revolutions. Humans are fragile passengers even if they do not hold the controls of the vehicle. For the case of the UAS/PAV, the humans are very much like those who enjoy air travel today. The substitution of the human pilot by a computer does not change the range of environmental conditions that the passengers experience. For the case of deep space, the environment will be quite different than any previous human spaceflight experiences and certainly quite different than air travel.

As mentioned above, the ISS does not offer a true representation of deep space conditions. A “Test Like You Fly” philosophy will drive demand on new testing facilities beyond LEO, where environments are far more relevant to deep space conditions. The lunar surface provides a more suitable analog for living conditions on Mars than does the ISS. Like the spacecraft, humans will train in the Mars analog in hopes of reducing the number of unknown unknowns currently associated with human space flight beyond LEO.

As in the early days of human space flight, ground and flight testing will lead to new applications of empirical data to improve spacecraft designs and keep the crew safe. Government agencies will leverage resources for advancing U.S. presence beyond LEO to protect commercial investments there. Advances in bioastronautics and aerospace medicine may play a major role, along with improvements in GCR shielding and artificial gravity, to extend the number of days that crew may stay beyond LEO, yielding a redundant pathway towards improved reliability and mission success.

Like mean time between failures (MTBF) tracked for spacecraft systems, each crew will be measured for exposure levels to GCR and microgravity and placed in remediation protocols before exceeding lifetime proxy limits. Remediation protocols may require in-space virtual doctors and real medical facilities rather than returning the astronaut to Earth-based facilities.

The lifetime proxy limits, possibly in the form of deep space exposure tables, will be established by ongoing experiences in space, including missions at Mars analog field stations such as on the lunar surface or in lunar orbit. As more is learned about the combinational effects, the exposure limits will be adjusted and deep space exposure tables updated, much like the changes over time to the scuba dive tables. It is only by “Test Like You Fly” that confidence in system reliability, safety, and performance can be truly realized.

Certification Strategy Built on Phased Pieces of Increasing Complexity

Human operations in space typically cost the order of 500 to 1000 times more than robotic, autonomous ones and must include sizable, expensive additional systems to keep humans alive and healthy. Therefore, for both financial and sociological sake (i.e. the societal impacts of loss of crew), it is essential that extensive efforts be undertaken to increase the safety and reliability requirements associated with humans in space.

The question is, of course, what safety level is required for humans in space and for what purpose. Explorers presumably are more risk tolerant than space tourists. That understanding may be the key goal to any certification process for both the aeronautics and space sides requiring orders of magnitude in improvements in safety.

It is recognized that all potential sources of failures, or their expected order of occurrence based on any likelihood correlated to statistics mentioned above, cannot be accounted for up front in the system designs. So, just as trust must be earned, so too will reliability and therefore safety.

Starting with the system complexity that is most familiar and understood, then adding in more features as lessons are learned during experiments at risk postures that do not expose the human element to unreasonable risk, seems the most prudent strategy. Below are some principals that may define that strategy:

- Due to the developing state of numerical and analytical testing approaches, and the ever-present possibilities of real-world unknown unknowns, physical testing should be the favored gold standard approach, in as complete a representation of the final system design and set of environmental and performance conditions as feasible.
- Serious literature studies and historical data should be employed to inform problem and solution spaces and their performance expectations.
- Producing orders of magnitude in improvements in safety and reliability will require consideration, evaluation, and testing of effects, conditions that are usually, hitherto been treated as secondary and noncritical or unimportant. Such improvements constitute new frontiers.
- Most serious issues are cascading failures and involve individually subcritical interactions or changes in multiple subsystems. This requires extensive testing of the final configuration and the system of systems to obtain definitive results.
- Individual technologies for specific issues should be tested piecemeal initially before incorporation.
- Analogues, such as those discussed previously, are usually used to gain insight and document trends, as well as to verify, or not, expectations.

One thing is clear. No matter the analogs created along the route toward certification, the threat of loss of life will be an uppermost consideration. Hence, planning and budgeting play key roles. Both will change with political environments and potential races to be first. Much will be learned. The question is at what expense.

Concluding Remarks

We are in the midst of simultaneous IT, bio, nano, quantum, and energetics technology revolutions. These technologies, when applied to aerospace, are enabling huge new markets, including UAS, the long sought-after PAV, and a plethora of deep space commercial activities. These markets are potentially very major, but currently nascent, and their equipment is developing in real time. They face serious safety and performance issues which include: crash statistics for less than the usual commercial aircraft statistics, necessitated by the expected huge numbers of vehicles, and the enabling ATC system for such numbers of aircraft. Issues for commercial deep space include: the increasing space debris, humans-in-space health issues, and space access rocket reliability. High levels of reliability and safety, and the enabling system performance to pay for them, are forward work. The narrative herein discusses the nature of these issues and posits prospective cogent solution spaces.

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)
- 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
- Analysis/prevention of cascading system failures

Overall – safety and reliability as a prime metric from materials, design through manufacturing, operations, maintenance, monitoring, and throughout the life cycle at the systems of systems level.

References

1. Bushnell, Dennis M., Enabling Electric Aircraft Applications and Approaches, NASA /TM-2018-220088, 2018
2. 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
3. Moses, Robert W., et al “Maintaining Human Health For Humans-Mars”, AIAA paper 2018-5360, 2018
4. Bushnell, Dennis M., Cosmic Beachcombing”, Professional Pilot, Dec. 2017, pp. 12-14
5. Oster, Clinton V. & Strong, John S. & Zorn, Kurt, 2010. Why Airplanes Crash: Causes of Accidents Worldwide, <https://ideas.repec.org/p/ags/ndtr10/207282.html>, 51st Annual Transportation Research Forum, Arlington, Virginia, March 11-13, 2010 Transportation Research Forum.
6. Wild, Graham, Murray, John, Baxter, Glenn “Exploring Civil Drone Accidents and Incidents to Help Prevent Potential Air Disasters”, Aerospace, 2016, 3,22, <https://www.mdpi.com/2226-4310/3/3/22>
7. Williams, Kevin W., A Summary of Unmanned Aircraft Accident/Incident Data: Human Factors Implications, DOT/FAA/AM-04/24, Dec. 04, <https://apps.dtic.mil/dtic/tr/fulltext/u2/a460102.pdf>
8. Asim, Mohammad, Ehsan, Nadeem, Rafique, Khalid, “Probable Cause Factors in UAV Accidents Based On Human Factor Analysis And Classification System”, 27th International Congress of The Aeronautical Sciences, 2010, <https://pdfs.semanticscholar.org/9963/90462b3baa7a7fa50584ef021a66035dd98a.pdf>
9. NASA, ‘Significant Incidents & Close Calls In Human Spaceflight’, https://spaceflight.nasa.gov/outreach/Significant_Incidents.pdf
10. Huber, Mark “Sikorsky Exec Stresses Urban Air Safety”, 2018, <https://www.ainonline.com/aviation-news/general-aviation/2018-05-01/sikorsky-exec-stresses-urban-air-safety>
11. Battcher, Duane “ 9 Essential Facts About Drones”, Property casualty.com, Dec. 5, 2017, <https://www.ainonline.com/aviation-news/general-aviation/2018-05-01/sikorsky-exec-stresses-urban-air-safety>
12. Hansen, George, et al , “Reliability Of UAVs and DRONES”, DSIAC, Spring 2017, Vol 4, no 2, <https://www.dsiac.org/resources/journals/dsiac/spring-2017-volume-4-number-2/reliability-uavs-and-drones>
13. Susini, Alberto, “A Technocritical Review of Drones Crash Risk Probabilistic Consequences And Its Social Acceptance”, Nov., 2015, RIMMA Conference, Berlin. https://www.researchgate.net/publication/291697791_A_Technocritical_Review_of_Drones_Crash_Risk_Probabilistic_Consequences_and_its_Societal_Acceptance
14. Embry-Riddle , “Drones Pose Increasing Risks To Aircraft”, Oct. 2018, UAS vision.com, <https://www.uasvision.com/2018/10/29/drones-pose-increasing-risks-to-aircraft-embry-riddle-study-confirms/>
15. Schrage, Daniel P., Functional Safety Management [FSM] For Complex Engineered Systems”, 6th International Conference And Exhibition Mechanical & Aerospace Engineering, , J. of Aeronautics & Aerospace Engineering, , 2018, V. 7,

- <https://www.omicsonline.org/proceedings/functional-safety-management-fsm-for-complex-engineered-systems-99159.html>
16. National Academy Of Engineering “Assessing The Risks Of Integrating Unmanned Aircraft Systems Into The National Airspace System”, National Academies Press, 2018, [available at <http://nap.edu/25143>
 17. Ocampo, Robert P. and Klaus, David M. “A Quantitative Framework For Defining “How Safe Is Safe Enough?” In crewed Spacecraft”, New Space, Vol. 4, No. 2, May, 2016
 18. Kroger, Wolfgang, Emerging Risks Related To Large-Scale Engineered Systems”, International Risk Governance Council, 2010, http://www.irgc.org/wp-content/uploads/2012/04/Large_scale_engineered_systems_Kroeger.pdf
 19. Sanchez-Silva, M and Klutke, G.-A, “Reliability Of Engineered Systems”, Chapter 2 in Reliability and Life-Cycle Analysis of Deteriorating Systems, Springer, 2016,
 20. Lum, Christopher W. et al “Assessing and Estimating Risk Of Operating Unmanned Serial Systems in Populated Areas”, AIAA Paper 2011-6918, Sept. 2011.
 21. Lum, Christopher W. and Waggoner, Blake “A Risk Based Paradigm and Model For Unmanned Aerial Systems In The National Airspace”, AIAA paper 2011-1424, 2011
 22. Paulitsch, Michael, et al, “Evidence-Based Security In Aerospace”, [2012 IEEE 23rd International Symposium on Software Reliability Engineering Workshops](https://ieeexplore.ieee.org/document/6405409), <https://ieeexplore.ieee.org/document/6405409>
 23. Stamatelatos, Michael et al “Probabilistic Risk Assessment Procedures Guide For NASA Managers and Practitioners”, NASA /SP-2011-3421, Dec 2011
 24. Bushnell, Dennis, “Autonomous Systems”, Professional Pilot, Dec. 2015,
 25. Bushnell, Dennis, “A Systems Approach To Enable Trusted Autonomy”, Professional Pilot, Nov. 2016,
 26. Button, Keith, “Wringing Out The Risks”, Aerospace America, March 2018, ppgs 17-21
 27. FAA, “Guide To Probability Of Failure Analysis For New Expendable Launch Vehicles”, Version 1, Nov. 2005
https://www.faa.gov/about/office_org/headquarters_offices/ast/licenses_permits/media/Guide_Probability_Failure_110205.pdf
 28. Podofillini, et al Editors “Safety And Reliability Of Complex Engineered Systems”, Sept. 2015, Proceedings of the 25th European Safety and Reliability Conference,
 29. Kreinovich, Vladik, “Reliability Analysis For Aerospace Applications: Reducing Over-Conservative Expert Estimates In The Presence Of Limited Data”,
<http://www.cs.utep.edu/vladik/slides/moscow11industry.pdf>
 30. TAI, Jimmy, et al, “An Assessment Of a Reaction Driven Stopped Rotor/Wing Using Circulation Control In Forward Flight”, AIAA paper 96-5612, 1996
 31. Lum, Christopher and Tsukada, Dai, “UAS Reliability And Risk Analysis”, Encyclopedia Of Aerospace Engineering, John Wiley and Sons, 2016
 32. Shih, Ann T, et al “NASA ARMD Technology Influence On Future Aviation Safety”, NASA /TM-2018-219827, 2018
 33. NASA, “Risk and Reliability”, ESAS, https://www.nasa.gov/pdf/140639main_ESAS_08.pdf
 34. Salotti, Jean-Marc, “Manned Missions To Mars: Minimizing Risks of Failure”, Acta Astronautica, V. 93, January 2014, pp. 148-161
 35. Barth, Tim, KSC/NASA Engineering and Safety Center, “Safety First; Safety for All,” Recurring Themes from Human Spaceflight Mishaps During Flight Tests and Early Operations, 8th IAASS Conference May 18-20, 2016,
<https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160009174.pdf>
 36. White, Julia D., Enterprise Mission Assurance Corporate Chief Engineering Office, “Test Like You Fly: Assessment and Implementation Process,” AEROSPACE REPORT NO. TOR-2010(8591)-6, January 18, 2010, Prepared for: Space and Missile Systems Center Air Force Space Command 483 N. Aviation Blvd. El Segundo, CA 90245-2808, Contract No.

FA8802-09-C-0001, <http://aerospace.wpengine.netdna-cdn.com/wp-content/uploads/2015/04/TOR-20108591-6-Test-Like-You-Fly-Assessment-and-Implementation-Process.pdf>

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) 1-04-2019		2. REPORT TYPE Technical Memorandum		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Reliability, Safety and Performance for Two Aerospace Revolutions--UAS/ODM and Commercial Deep Space				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Bushnell, Dennis M.; Moses, Robert W.				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER 736466.01.01.07.01	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NASA Langley Research Center Hampton, VA 23681-2199				8. PERFORMING ORGANIZATION REPORT NUMBER L-21007	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001				10. SPONSOR/MONITOR'S ACRONYM(S) NASA	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) NASA-TM-2019-220274	
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified- Subject Category 01 Availability: NASA STI Program (757) 864-9658					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Aerospace is in the midst of a Renaissance, expanding on both the air and space side into major new commercial areas including UAS/PAV and commercial deep space. These new areas require, in the initial planning, consideration of new safety, reliability and in some cases enabling performance approaches for viability. As examples if due to their huge numbers UAS/ODM aircraft start falling out of the skies at an unacceptable rate, causing life and property damage, if humans in commercial space activities have serious health issues and/or there are unacceptable rocket viability issues/ crash rates, these new, major [order of \$1T/yr.] markets could be rapidly curtailed until agreeable and effective changes are instituted, producing yet more expense, delay, reduced revenue. The present work addresses such issues, including some performance enhancement possibilities, for initial consideration going forward including the enabling ATC, crash proof vehicles, increased range for Aero, and for space, debris removal, human health and rocket reliability.					
15. SUBJECT TERMS Aerospace; Crash proof; Health issues; UAS/PAV					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk (email: help@sti.nasa.gov)
U	U	U	UU	29	19b. TELEPHONE NUMBER (Include area code) (757) 864-9658