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ATM For Many Millions of Flying Things: An Alternative Approach

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Air Traffic Management For Many Millions of Flying Things: An Alternative Approach

Dennis M. Bushnell

Introduction

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: drones. Drones, or Unmanned Aircraft Systems (UAS), have a prospective market value above $1 trillion per year, doubling civilian air markets (ref. 1). This UAS/drone component 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 drones, civilian aircraft were piloted by humans and numbered in the thousands. UAS 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. These technologies include greatly improved durability nano printed materials with superb microstructure, printing manufacture, autonomy, electric propulsion, and advanced batteries/fuel cells, along with the economies of scale. There are currently a plethora of UAS vehicle designs in development that are aimed at human carriage for urban air mobility, on demand mobility, and Personal Air Vehicles (PAV) (ref. 2). Going forward, these technologies proffer autonomy and electrics for ever increasing vehicle size and speed, even up to supersonic (ref. 1). The low cost of these new aviation machines will result in many tens of millions of them taking to the skies. A majority of them will operate over developed and populated areas, potentially posing a safety concern (ref. 3).

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 4). The current consensus appears to be that, while nearer term modifications and additions will aid air traffic management for the initial introduction of UAS, Urban Air

Mobility (UAM) the current system (ref. 2), 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. 5). The latency issue revolves around the human-controller-centered nature of the current Air Traffic Management (ATM) systems. Worldwide, the current, nearer term UAS 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 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 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 cyber-attacks, Electro-Magnetic Pulses (EMP), and jamming. The developments in flow control for air vehicles are proffering nearly all weather operation, necessary as transportation, with UAS, becomes much more "airborne".

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 writ large, collision avoidance, trusted autonomy, detection and control of non-cooperating air vehicles, resilient communications, an architecture that involves cooperative information sharing across all components, and the requisite Artificial Intelligence (AI) and computational equipage. For the longer term with tens of millions of flying things, a wholly new single autonomous ATM system is required. It should be capable of rapid and inexpensive development and other requisite attributes. 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, have to 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 PAV buildout. The nominal time frame for such a new system to go live, should be the order of some 5 to 10 years or so. It will be dictated by the rapidly evolving UAS markets which will require air space access for on the order of a trillion dollar new aero market, including replacing automobiles.

The overall suggestion discussed herein 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 (ref. 1). The initial development of such a simulation began in the NASA "Smart NAS [National Air System]" effort (ref. 6). 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 wholly new ATM system. This report discusses the various piece parts and their options to develop a nearer term, affordable, safe replacement ATM system that would enable tens of millions of flying things.

Replacing large segments of ground transportation with PAV will:
- Greatly reduce ground infrastructure investments in roads and bridges which are no longer adequate and which we cannot afford to repair.
- Could, if we do it right, result in less loss of life than on the roads with human operators.
- Will be a revolution in personal transportation, enabling us to go anywhere, anytime, up to transcontinental, especially since most scheduled airline trips are 500 miles or less; PAV will obviate most of scheduled airline business and obviate the time/treasure associated with dealing with ground traffic.
- Will enable wider distribution of the population, reducing the flooding, desiccation, and heat islands produced by population concentrations.

The purposes of this report are:
1. To raise consciousness that the current UAM/AAM (Advanced Air Mobility) research is not addressing the huge buildout markets of PAV, many tens of millions instead of tens of thousands. These markets, in terms of vehicles and market/intention wise are developing rapidly. What is not considered seriously thus far for many tens of millions of PAV are the major infrastructure issues, as stated in the recent Academy report (ref. 4). The major infrastructure issues are ATM and safety.
2. To indicate that the current UAM plans for tens of thousands of vehicles via evolutionary changes to the current ATM will not address the PAV requirements, which require a wholly new, totally autonomous system developed in the time frame of the market development.
3. Suggest an overall approach to the enabling PAV ATM that is a shortcut around the evolutionary approach to such.
4. Provide some putative approaches to the requisite techs; consider different approaches that could result in new opportunities.

The Requirements

The requirements that dictate the need for and capabilities of a new, albeit morphed, PAV-class ATM system include the following:

- Ongoing development of capable and affordable UAS designs for a multiplicity of government, commercial, service tasks, and eventually a PAV replacement for the automobile with prospective markets in the tens of millions of flying things. The current air fleet is in the thousands. The current UAM research planning is in the tens of thousands. The putative markets for UAS including PAV are estimated in the trillion dollar level, doubling the commercial/civilian aero market value.
- These UAS will operate across the altitude range and largely over developed areas with diverse vehicle types and capabilities across the speed range.
- Control of such huge numbers of air vehicles, in what will become very congested and dynamic air space over large developed areas, is beyond the capability of human air controllers. What is required is latency and safety only available from autonomous robotic systems, for both ATM and the vehicles. Historically, some 80% of aerospace accidents are associated with/due to human factors.
- Typically, these UAS will operate largely quasi-randomly from/to multitudinous locations in the countryside, including individual holdings, instead of from "airports".
- Superb communications are required between the ATM system and the flight vehicles to exchange sensor data, intentions/directions, and for control.
- To the extent possible, systems should be "fail-safe," including the piece parts, with robust, scalable capabilities.
- Crucial technologies and integrated piece parts include trusted autonomy, navigation, sensors, flow control for all weather, safety, electron security, and the requisite architectural approach.

A new ATM system should be capable of affordably and safely controlling numbers of flying things in the tens of millions over all altitudes, vehicle types, with quasi-random takeoff, landing and operations locations, and including National Security Air Traffic. From a market development standpoint, such an ATM system is required on the order of 5 to 10 years (versus decades), without its development interfering with the operation of the current ATM system. The technologies to enable and execute such a requisite ATM system are either available or rapidly developing. What is needed is the foresight with regards to what the rapidly developing UAS markets will require of an enabling ATM system. It will also need the courage to work the much less expensive, far shorter, and much safer approach of a wholly new system instead of attempting to morph the existing, wholly inadequate for the projected markets, system. Because ATM, increasingly going forward, will be co-operative with regard to both a central system/distributed systems and flying vehicles, this report considers capabilities and equipage that is ATM related on both vehicles and central/distributed ATM systems.

Trusted Autonomy

Autonomy refers to systems that are designed to operate, after tasking, without direct human direction/intervention, including handling unanticipated events (aka "unknown unknowns"). The foremost component of autonomy is AI, which has emerged as extremely useful and increasingly capable. This is after decades of inadequate computing capability (no longer true) and a diversion into expert systems, utilizing now and since the early 2010s neural nets/deep learning and "big data". Going forward, there is progress in nanosectioning the neocortex and replicating it in silicon as an alternative, possibly approaching a biomimetics or human level path to AI. Then there is emergence, the process of making things complex enough that they can "wake up". This is the suggested source of human intelligence via evolution over millions of years.

Trusted autonomy is required for the frontier Air Traffic Control (ATC) system described herein. This autonomy should be able to handle, successfully work through, unknown unknowns and untoward events (ref. 7). Such autonomy requires machine ideation, which is not yet off-the-shelf extant. In aeronautics, the prime reason pilots are still used to transport people is because they are considered necessary to handle untoward circumstances, or unknown unknowns.

The fundamental aspects and precepts of trusted autonomy are safety, security, reliability, and resilience for both on design and off design. On design refers to the functionalities and states required to execute the design mission, and off design refers to conditions and operations at other than those included in the parameters and conditions for design operability.

For design missions involving the usual architectures and technologies and having a considerable historical experience base, most of the issues required to be satisfied are knowns. However, as new/unique technologies are employed and/or for new or unanticipated mission conditions and functionalities there arises—especially for off design—the specter of both known unknowns and unknown unknowns.

Autonomy, increasingly applied to an ever broader spectrum of conditions and functionalities, subsumes the conditions of both new technologies and new/unanticipated operability conditions. This requires trusted autonomy due to the potential presence of known unknowns and unknown unknowns. An obvious overarching example of a known unknown requirement to be considered for all autonomous systems going forward is the preservation, or not, of electronic operability—the bedrock requirement for autonomy. There is also an increasing number of issues with regard to electronics.

Thus, trusted autonomy (i.e., systems fully operated by machines) requires the identification of, and solutions spaces for, untoward events, conditions/occurrences beyond the operational automation functionalities and design, along with associated system functionalities capable of accommodating such in a safe manner.

Suggested is a combinational approach involving ab initio system design for knowns and as many known unknowns as possible, as well as an on-board resilience system which both evaluates threats and determines, makes operational, and executes system responses utilizing the full panoply of system capabilities in order to ensure safe operations and trust in machine-operated systems.

An obvious way forward is to minimize the number of unknown unknowns and maximize the number of knowns so that most off design conditions can be dealt with via the ab initio design and the associated operational AI system—if that is determined to be efficacious. The rest can be dealt with by an on-board resilience system. The obvious key to doing such is data, information, knowledge of everything (literally anything/everything) connected with the system and its surroundings, including potential and actual variations thereof. Also included in this is the knowledgeability of combinational interactions up to the systems of systems level. Identification and treatment of untoward events begins with as complete as possible a systems operational specification. This includes initial, boundary, and environmental conditions as a function of space and time. This establishes the system's operational functionalities and environment, and the parameterization that both constitutes the design space and provides the specification of the design's normal conditions, which can then be investigated for off normal/off design. It is essential to document all assumptions made throughout so that these can be scrutinized for correctness and obviated as a potential untoward if that is conceivable.

For autonomous aviation, untoward events could include combinations of weather issues, traffic, the health of the vehicle's systems along with its degradation and limits, and the many safety issues associated with human factors—if such vehicle is not fully autonomous. Presumably, an autonomous system should—and could—be safer via obviation of human factors, errors, latency, etc. However, autonomous operations are typically held to much stricter standards than manned operations. Many thousands are killed on the roads by human operated automobiles and in hospitals by human actions. Society would not allow such safety performance in an autonomous system.

An overall essential capability to design and operate trusted autonomy aviation systems is the recently developed and still undergoing maturation combination of big data, deep learning, neural nets, and sizable/capable computing machines. An early poster child for this capability was the IBM Watson device, and more recent instantiations are being applied across a broad range of issues including medicine. Implementation has been very successful, in many instances constituting a narrow AI niche with, at, or beyond human capabilities. Such a capability knows far more than individual humans, obviates the many sources of human error, has much reduced latency, and has many other favorable attributes. Given sufficient information, this big data/deep learning approach could:

- Determine to the extent possible the potential known unknowns and the unknown unknowns.
- Conduct a risk assessment and estimate which of these risks can be included in the ab initio system design as additional to the usual on design functionalization. This includes self-repair. Usual risk assessment approaches include probabilities and potential system impacts writ large.

Other issues identified but not directly included in the vehicle design are carried over to be dealt with by an on-board resilience system. This on-board resilience system consists of an on-board AI system which continually updates the data across the board and determines extant and emerging potential threats/problems. Using Thaler Machine ideation (ref. 8), it determines solution/coping spaces, decides which is most efficacious, and executes the solution spaces to preserve lives and property. An important aspect of this approach is that an overall aviation corporate memory is built up via such interactive communications/learning. Thus, the envisaged resilience system is broadly capable and knowledgeable, not limited to a particular aircraft or type of aircraft.

Such an on-board resilience system would be given authority to utilize the entire vehicle system capabilities to develop and execute solution spaces for untoward problems, which were not included in the ab initio system design. The intent is that the resilience system enables the aircraft to fly while hurt. This capability is related to current NASA research efforts termed “Learn To Fly” and “Safe To Ditch,” etc. (ref. 9).

This overall approach uses AI to both improve the initial design and improve reliability/resilience/safety (over and above the automation of the on design vehicle functionalities) via a continually updated on-board lifeboat resilience system. It should provide trusted autonomy to a level such that humans would no longer be required for operation. This, as already stated, would obviate the large panoply of human factors errors, thereby further ensuring and improving safety.

The major key to such an approach to trusted autonomy, which will only improve as AI further develops, is defining which/what is subsumed in the initial design and continually updating both off-board and on-board “big data” sets.

Some obvious cogent databases include:

- Weather: Predictions and combinational historical extremes associated therewith.
- Integrated vehicle health management, including on-board sensors for vehicle health assessment/management of all systems, including structural.
- Aircraft traffic/ATM data. This includes projections to inform potential collision possibilities and wake vortex hazard issues, which enables constant planning of avoidance maneuvers.
- Documentation of aviation accidents and near misses of any kind, both civilian and military, worldwide, along with appropriate or actualized solution/obviation approaches. Those who do not study history are consigned to repeat it.
- Reliability data analyses for all vehicle components and systems.
- Complete performance specifications of system design parameters, individual components and as systems of systems.
- Details concerning potential terrorist attacks of any type.
- Potential cyber and EMP issues, threats and potential impacts, and known workarounds.
- Redundant navigation approaches, positioning.
- Complete digital twin data bases as available.
- Communications functionality.
- Bird prevalence, sizes.
- Aircraft security sitrep.

These databases consider, address, and subsume the usual sources of aircraft accidents including pilot error (responsible for some 50% of all aircraft crashes), mechanical error (22%, includes some components of human error), weather (12%), sabotage/terrorism (9%), and other human errors including ATC and human-caused fuel starvation (7%) (ref. 3).

Machine Ideation

Currently, AI is predominately deep learning utilizing big data that does not yet create/ideate ab initio. Steve Thaler (ref. 8), and over the years others, have developed an approach to machine ideation for evaluation of, and solution spaces for, untoward events necessary for improved trusted autonomy. Thaler developed, has long deployed and improved an imagination engine wherein he trains a neural net and then deprives it of rational input. The neural net cavitates, in some sense “dreams,” akin to humans dreaming, and in the process produces quasi-random combinatorials, again in a fashion akin to the human subconscious. These quasi random combinatorials are then, with machine speed and knowledge, evaluated as solution spaces for various problems and metrics at the systems level and better. Machines enable parsing, evaluation of a huge number of potentially useful combinatorials in a time frame many orders of magnitude faster than could humans.

This approach, generation and evaluation as a solution space of huge numbers of quasi-random combinatorials, has enabled ideation via brute force, not AI per se, of a plethora of possibly useful solution spaces. Machines are now of sufficient capability to enable incorporation of this brute force ideation approach into a trusted AI system to provide and ensure solution of unknown unknown issues as they arise, as the keystone of a reliability adjunct to an autonomous operating system.

Communications/Electron Resilience

Autonomous operation of both air vehicles and the ATM system requires superb connectivity and a ménage of electronics including sensors, communications equipment and approaches, computers, actuators, navigation, etc. Air transport, as well as society as a whole, is wholly dependent upon electrons. Unfortunately, electrons are increasingly vulnerable to various operational, natural, and criminal/terrorism issues. Solar storms and such as flux compression generators can produce EMP that disables (or worse) the electronics. Cyber-attacks are endemic and too often successful. Use of the E-M spectrum enables jamming. Recourse to optical systems, using photons instead of electrons could mitigate these vulnerabilities, since protons are much more difficult to jam (with the exception of locally with aerosols). As the photons connect to electronics, the electronics would still be vulnerable to cyber and EMP threats. There is a new approach that is not E-M but instead a Quantum vector/scaler potential approach from Puthoff and others. It operates using principles from Aharanoff, Josephson Junctures, and to the first order, cannot be detected, jammed, or intercepted (ref. 10). There is now serious development ongoing of this wholly new comms approach which would hugely alter the vulnerabilities of communications and go through the water column at a high bandwidth.

Characteristics of the Puthoff Non E-M approach include:

- U.S. Patent 5,845,220 [12/98]

- Scalar waves only, E-M fields suppressed/canceled
- Penetrating & non-shieldable
- Far Field decays as 1/r vice 1/r**2
- Requires quantum detectors (e.g., Josephson Junction)
- Non-detectable by ordinary E-M devices
- Enables high bandwidth comms through the air-water interface

Otherwise, for E-M based systems, could need faraday cages and decouplers for EMP protection, frequency hopping/LPI (low probability of intercept) to avoid jamming and the latest in cyber security to ensure continued operability. Then, there are operational issues, equipment failures, etc., which, although becoming less frequent, require resilient electronics equipage.

Navigation

The conventional, usual navigation approach has been the Global Positioning System (GPS), which is ever more accurate. However, GPS has very low signal strength and therefore is easily jammed and co-opted. Therefore, alternative/redundant navigation systems are required. The obvious alternative is utilization of stationary E-M signal sources such as TV, radio, MW towers, etc. These typically have signal strength several orders of magnitude greater than GPS and their multiplicity ensures accurate navigation and their use would be straightforward. Another alternative navigation approach is cold atoms, also termed atom optics. A Bose-Einstein condensate of atoms at the same quantum state is manipulated to provide inertial navigation at some three orders of magnitude better than the usual inertial systems. The Air Force is developing this. Optical GPS appears to be executable and its lasers would be much more difficult to jam, but there have not yet been efforts to develop such. Then there are two enablements from the extensive Earth scrutiny from orbit/space, combined with much more capable quantum sensors, utilization of gravity, and magnetic mapping details. These are akin to the earlier tercom used on cruise missiles employing geological surface feature mappings.

Sensors

Up to date detailed data with regard to all vehicle capabilities, positions, velocity vectors and amplitudes, vehicle intentions, operational status, etc. are required for a successful ATM system. Going forward, that data must be acquired by sensors on the vehicle, in space, and anywhere feasible for redundant coverage. Nano and quantum sensing capabilities are developing rapidly in great numbers, comprising what is projected to be a global sensor grid within 10 years and involving trillions of sensors. These sensors are collectively multiphysics and therefore very hard to spoof, with ever increasing coverage, sensitivity, and resolution. They will provide really big data for the AI systems and should have the redundancy to provide robust requisite data streams.

Sensor trends include:

- Mini-to-Micro-to-Nano-to-atomic
- Hyper-Spectral
- Multi-physics
- Hyper-Sensitive
- Hyper-Resolution
- Integrated with actuators, processors, comms
- Sensor Webs/Swarms/Networks
- Inexpensive
- Lower power, energy harvesting
- Brilliant
- Ubiquitous
- Data fusion/sense-making
- Wireless
- Apertures from Co-op conops and membranes
- Active and passive

Flow Control

As personal transportation shifts to a reliance upon personal air vehicles from automobiles, it is more than desirable to have at least the automobile level capability to operate in challenging weather, and possibly better. Floods and deep snow and icy roads affect autos more than aircraft, but very high winds and heavy rain could affect aircraft more than autos. The desirable air vehicle end state would be weatherproof. Extreme conditions such as tornadoes or hurricanes would cease operation for both autos and aircraft, but there are flow control technologies in development which could greatly increase aircraft operability in weather. The major issue is flow separation which reduces lift and can greatly, along with winds, affect controllability. There is a plethora of separated flow control approaches developed over the last century which are usually applied at takeoff to provide high lift, but are hardly ever utilized in cruise. Which, what of the available and developing separated flow control approaches to use for improved flight through weather is a systems tradeoff with regard to cost, weight, and effectiveness (ref. 11). Recent research on morphing surfaces provides an interesting approach to consider. Thrust vectoring is another effective control approach for high winds. For icing issues there are a variety of possibilities such as heating and surface chemistry subject to selection based upon systems issues. The bottom line with regard to much improved operations in weather for UAS class aircraft and for most other vehicle design issues primarily involves cost and safety in relation to the wealth of available technological approaches.

Safety

There are two requisite/pacing infrastructures that dictate the development timescale of PAV utilization/markets, ATM/airspace access, and overall safety. Major ATM related AAM/PAV safety related issues include collision avoidance, which is the avowed prime purpose for an ATM system. The extreme increases in traffic density associated with the PAV buildout requires complex optimized autonomous anti-collision approaches (ref. 12) coupled with multi-physics redundant precise navigation and sensors and enabling high bandwidth robust communication approaches. Along with raw traffic projections, what designs the anti-collision system is the huge numbers of PAV vehicles flying out of and into nearly random driveways, roadways, etc. to a nearly random set of destinations, akin to discordant swarms (ref. 3). Critical to all this is collection, utilization, and subsequent control of projected flight paths (i.e., anticipation of the dynamic future states to the maximum extent possible).

Natalia Alexandrov of NASA Langley Research Center has suggested that as traffic density and collision avoidance actions increase, the potential end state could be near Brownian Motion, with much time spent avoiding collision and little time spent on the flight path to the destination. Obviously required overall is resilient/fault-tolerant/high-reliability/fail safe systems. These systems should be capable of handling and controlling uncooperative vehicles, mechanical/other failures/issues in real time, with initial alertment as soon as possible from on-board or system internal diagnostics, and often ultra-small latency/unpredictable new vehicle entrants with variable flight capabilities. After equipment malfunctions, the greatest source of induced latency in the ATM system is the dynamic effectiveness of the vehicle control systems.

Historically, human ATM controller and pilot errors have been the prime causes of hazardous ATM related incidents, this even at the current thousands of flying things. At tens of millions of flying vehicles, autonomous systems are required (ref. 5). Even with the best software/algorithms/AI, there is always the possibility of software errors and emergent properties. This results in creating unknown unknowns, hence the suggested machine ideation resilience system.

Obviously part of safety, especially for those on the ground and ground infrastructures as well as the vehicle, are efforts to crashproof. This is done either by designs/on-board equipment to land gently or to morph the vehicle so that it keeps flying. Flying while hurt constitutes yet another design requirement.

ATM Architecture

The overall ATM architecture for tens of millions suggested herein has at its core a trusted autonomous anti-collision system. This system includes the many piece parts necessary for successful actualization such as communications, navigation, sensors, data/knowledge access including vehicle characteristics, weather, etc., and electron security. Needed is a distributed ground and space based system incorporating the "controlled" vehicles and continuous system/vehicles communications/updates. Prime vehicle control function is owned by the system, which is capable of taking control of/flying both compliant and non-compliant vehicles. Vehicles have a secondary control function for adjacent vehicles to cooperatively avoid collisions as a fail-safe anti-collision backup. The computing power and the technologies and AI to develop such a wholly new autonomous ATM system appear to exist or be developable soon enough to enable a timely PAV market.

The primary purpose of an ATM system is to avoid collisions. The PAV buildout will have vehicles popping up all over the place from driver's driveways, going to nearly random destinations, a very dynamic N body problem. What would help is traffic lanes in the sky but without stoplights (obviously), although with Vertical Take-Off and Landing (VTOL) that is possible. Otherwise the situation would degenerate to Brownian Motion as traffic increases. Airspeed and direction would have to be controlled for each vehicle, based upon a constantly changing optimization problem. Only machines can do this system of systems control problem and the system must have control of the vehicles. The worrisome latency is that of the control effectors and speed brakes on the vehicles. Flow control can be used to ensure they can keep flying, as well as the VTOL capability. The vehicles will have heterogenous capabilities, but that is just more details to load into the system, part of the requisite solution space.

Concluding Remarks

UAS now constitute an ongoing revolution in aeronautics. Like most of the many ongoing technology revolutions, UAS are at the scale and within the resources of the user down to the scale of the individual. Initial and ongoing UAS applications have thus far been primarily service related, for commercial, government, and individual needs. The now feasible buildout for UAS is a long sought individual level aspiration, a personal transportation air vehicle to replace the automobile. This will provide a revolution in individual mobility, operate out of an individual holding, and provide huge benefits with regard to automobile infrastructure savings. The result will be a new aero market the order of $1T/yr, doubling the current civilian aero markets. This PAV UAS buildout will result in tens of millions of air vehicles, which for airspace access requires a completely new and autonomous ATM system. This report outlines an approach and the piece parts for such a system that is possible and affordably developable within the market build out time frame of five plus years. An enabling ATM for this PAV market cannot be developed via extensions of the current human-centric ATM system due to latency, cost, and scalability issues. There does not appear to be an evolutionary path to a viable ATM system that is affordable, effective, safe, and within the PAV market build out time frame. This report posits one revolutionary approach to the requisite time, cost, and safety metrics for a timely, successful PAV buildout.

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