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Autonomous Civil Aircraft—Are They the Future of Aviation?

Herman A. Rediess
National Institute of Aerospace, Hampton, Virginia

Sanjay Garg
Glenn Research Center, Cleveland, Ohio

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Sanjay Garg
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National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

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Herman A. Rediess
National Institute of Aerospace
Hampton, Virginia 23666

Sanjay Garg
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Summary

As the Commission on the Future of the U.S. Aerospace Industry prepared to make its final recommendations, the Hon. Robert Walker, Chairman of the Commission, stated that the nation should consider possibilities that are too radical for current lawmakers to openly discuss – "As an example, I would hope that in our vision we would talk about the idea of maybe flying passengers on [pilotless] aircraft in the future. . . and having an air traffic management system which is so robust that it makes that possible." This article tries to address the issue of whether autonomous civil aircraft are the future of aviation? What is meant by the term "autonomous civil aircraft" is described followed by the discussion of the case "for" and "against" such aircraft. The technology and operational challenges to enable autonomous civil aircraft are then described. The article concludes with a suggested roadmap for making this future vision a reality.

What are Autonomous Civil Aircraft

The word *autonomous*, as defined in the dictionary, means *not controlled by others or by outside forces*. Based on a Naval Studies Board review of Office of Naval Research Uninhabited Combat Air Vehicles program, the term *fully autonomous* is described as *the system requires no human intervention to perform any of its designed activities across all planned ranges of environmental conditions.* For commercial aircraft operating in civil airspace, the term "*autonomous civil aircraft"* implies the capability to perform all the "typical" functions required for safe flight from a starting point to a desired end point, while flying in conformance with national airspace constraints, without having a human being in the control loop, either on-board or off-board (on the ground or on another air vehicle). The term "typical" is meant to differentiate *autonomous* with extreme cases where human intervention may be desirable. An example is the case of the Sioux City incident with flight UAL 232, where there was a catastrophic disk failure which led to loss of all hydraulics for flight control surfaces. The flight crew correctly diagnosed the problem, flew the airplane using engine thrust differential, and reached the airport safely, only to crash when a wing tip touched the ground on landing. A *fully autonomous* aircraft would be one that could have accomplished at least the same level of success as the pilots achieved for UAL 232. Some human monitoring of autonomous aircraft will be needed, at least in a transition period, to ensure that safe and secure operation is maintained in the presence of unforeseen circumstances, and that the systems are performing as expected in the presence of expected changes in environmental conditions—both internal (e.g., anticipated faults) and external (e.g., change in weather conditions). Autonomous aircraft must have sufficient on-board intelligence to determine when the system is overwhelmed and would like the human to take over, and communicate that to the human monitor/controller. The vision for truly autonomous aircraft is that the number of times humans take control per million flight-hours is significantly lower than the number of accidents per million flight-hours in transport aircraft in the U.S. today.

It is important to distinguish between autonomous aircraft and UAVs (Uninhabited Air Vehicles). The term UAV implies that there is no human on board the aircraft; however, typically current operational UAVs are controlled from the ground with one or more humans. The UAVs do exhibit some level of autonomy—mainly to the extent of being able to fly between points on their own, however, they are very far removed from being autonomous. This level of autonomy is akin to the automation that already exists on current aircraft, such as mission management integrated with autopilot to provide the capability to go from one point to another under "normal" conditions without direct human involvement. It is the capability to accomplish a varying set of complex tasks under reasonable changes in the operating environment and system capability which distinguishes *autonomous* from *automation*.

The Case For Autonomous Civil Aircraft

The short answer is to "exploit the tremendous benefits derived from highly mobile citizenry and rapid cargo transportation" as stated in the final report of the Commission on the future of the United States Aerospace Industry. Autonomous transports could reduce air cargo costs and transit time from origin to destination resulting in lower cost to consumers and stimulation of the economy. Autonomous commercial transports could lower the cost of mass air transportation making it affordable to a broader segment of the traveling public. Autonomous very-light jets could enable air taxis that are affordable for the general public for flexible and time-efficient door-to-door transportation. Autonomous general aviation (GA) aircraft could make available personal air vehicles to non-pilots for flexible and time-efficient door-to-door personal transportation and stimulate an "automobile-like" market for GA aircraft. Autonomous surveillance aircraft could provide new highly effective security measures and law enforcement, earth resource monitoring and preservation, forest fire early warning etc. Small, highly maneuverable autonomous aircraft can provide rapid delivery of small high-value packages, like hospital-to-hospital transportation of vital organs, and many other beneficial services.

If an autonomous short take-off and landing aircraft cargo system could fly directly from origin to destination operating out of industrial parks instead of airports, it would not only eliminate flight crew costs and minimize ground transportation costs, it would also reduce terminal area and airport air traffic congestion leaving more capacity for passenger transports. Emergence of the very-light jet has stimulated interest in air taxi services. Some aviation economists question the viability of air taxi services business with two pilots and consider it to be marginal with one pilot. Operating air taxis with no pilots not only reduces operational cost but also turns pilot seats into revenue passenger seats. There would be no crew costs for ferrying an empty aircraft to a customer or while waiting for customers to call.

The NASA Small Aircraft Transportation Systems program envisioned a future where GA aircraft were as easy to fly and as safe to drive as cars and that the general public would use aircraft routinely for personal door-to-door transportation. That is a vision of the autonomous GA aircraft operating in an automated airspace system. Consider taking a trip from Manassas, Virginia to Rochester, New York for a weekend visit with your daughter. You, a non-pilot, hop into your fractional ownership autonomous aircraft; select the most convenient or scenic route; engage the automatic flight management system and autopilot, which taxis, takes off and flies the aircraft to Rochester in less than an hour and one half after leaving your home. All this is accomplished without a pilot touching the controls or talking to air traffic controllers and at the same time millions of personal air vehicles are operating in a similar manner in the national airspace.

If the infrastructure could support millions of personal aircraft operating with the type of flexibility and freedom we enjoy with cars and do it safely, industry would develop the vehicles and market. As the market developed, automobile-type mass production might follow, driving the price down to the point where an ever-increasing segment of the population could afford personal air vehicles.

NASA Small Aircraft Transportation Systems Program Concept of Future General Aviation Aircraft.

The Case Against Autonomous Civil Aircraft

In the early 1950s, MIT Instrumentation Laboratory flew a bomber automatically from Massachusetts to California using a high-precision inertial navigation system. Pilots were on board but did not intervene. The military have operational UAVs that fly worldwide. Why aren't there autonomous civil aircraft today? First, it's one thing to fly one experimental aircraft autonomously across the country with virtually no traffic or use small numbers of UAVs in essentially 4-D special-use airspace for military missions; and, another to operate hundreds of thousands to millions of autonomous aircraft, many carrying passengers, operating night and day 365 days a year over heavily populated metropolitan areas in congested civil airspace. The safety issues are enormous, the technical challenges formidable and public acceptance is questionable at best. Resolving the technical challenges and assuring system-wide safety must be accomplished at an affordable price. Public acceptance has two aspects: passengers acceptance of flying with no pilot; and, the general public acceptance of multitudes of pilotless aircraft flying over major cities and their homes.

The airspace and airportal infrastructures were not developed with autonomous operations in mind and are unlikely to be sufficiently reliable to support fully automatic flight and air traffic management safely. The infrastructure and associated air traffic management (ATM) procedures were developed for human operators and have several levels of human-in-the-loop backup systems in case of failures. Piloted aircraft systems have been developed to operate safely within this human-centric infrastructure. UAVs are required to have a remote pilot who can communicate with air traffic controllers and command trajectory changes to operate within the National Airspace System (NAS). To add sufficient redundancy to the existing infrastructure and aircraft systems to enable safe autonomous operations could be a prohibitively expensive venture, making it infeasible to implement in our lifetime. If human monitoring and remote takeover control capability is required for millions of autonomous aircraft at all times, the communications requirements (unique frequencies and secure) may be impossible and the cost of qualified pilots monitoring operations and prepared to takeover may negate any advantages of no pilot onboard.

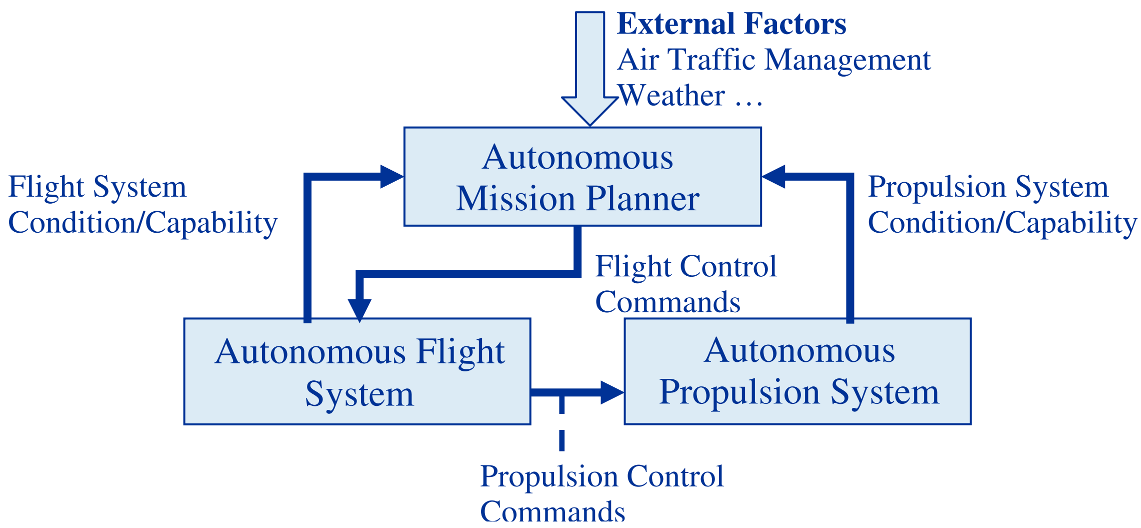
The Technology Challenges

Advancements in flight management systems coupled with an autopilot make it possible to fly an airplane *automatically* between previously designated points under “normal” conditions. For airplanes so equipped, the pilot needs to take over control for any “off-nominal” conditions such as rough weather, special airport operational requirements, system fault or malfunction, damage or loss of control etc. Having complete autonomous flight operations of aircraft throughout the operating envelope and under various operational conditions will therefore require further development of control, diagnostics and mission planning systems capable of handling the off-nominal conditions that are currently performed by the human operator. An “Intelligent On-Board Mission Planner” will need to decide based on internal (condition of the aircraft and subsystems) and external (weather etc.) conditions whether a given mission (flying from point A to point B on a given trajectory) is achievable or it needs to be modified (such as either change trajectory to avoid poor weather or change landing point for safety). An intelligent control system, which adapts to changes in the vehicle dynamics and reconfigures itself for potential subsystem malfunctions (such as partial control surface failure etc.) will be needed to ensure that the mission objectives are achieved. Reliable diagnostics and prognostics for critical aircraft subsystems which affect mission success will need to be developed to support the intelligent control and mission planning. Implementation of these intelligent adaptive systems will require development of new methods for verification and validation of the functional design as well as the associated software. Avionics hardware advancements will be necessary for the higher computational and communication requirements for the distributed control architectures needed to implement these intelligent systems.

From a functional perspective, the three critical elements and their interaction for enabling autonomous aircraft flight are shown in the attached figure and discussed in the following. An operational challenge for autonomous flight will be to decide what information needs to be communicated to the human monitor to decide when to override the autonomous system.

Autonomous Mission Planner

For autonomous aircraft, mission planning will include not only trajectory and path planning for a given mission, but also the capability to adapt the mission due to changing circumstances such as adverse weather, new directive from air traffic control, damage to sub-system etc. Although a lot of research is being conducted on autonomous trajectory/path planning for UAVs, very little work is being done on doing such planning under situations where the aircraft has reduced performance capability. As shown in the figure, the autonomous mission planner inputs will consist of those external to the vehicle (weather, air traffic management needs etc.) and those internal to the vehicle such as the current performance capability of the flight and propulsion systems. Technologies that make effective use of this information in real-time to assess various mission scenarios and decide on the one that best meets the mission objective while maintaining the safety of the aircraft will need to be developed and validated. Just as a pilot makes a decision to land the aircraft at a nearest airport in situations such as loss of an engine, or loss of cabin pressure etc., the autonomous mission planning should be capable of making a similar decision which can then be collectively implemented by the autonomous flight control and the autonomous propulsion system. A critical factor in acceptance of such autonomous mission planning systems will be their capability to execute complex tradeoffs in near real-time and have predictability and reliability of decisions.



Control Architecture for Autonomous Aircraft

Autonomous Flight System

As mentioned earlier, currently operational UAVs have demonstrated a reliable capability to fly automatically, under "nominal" conditions, between designated points based on pre-planned trajectories, such as following waypoints, avoiding certain areas etc. The technologies needed to be able to accomplish this objective when there are sub-system faults or damage to the aircraft which results in changed dynamic behavior remain to be developed and demonstrated. Although there has been tremendous research in the area of intelligent flight control, which adapts the flight control for damage to the aircraft, the focus of these efforts has been to leverage the control effector redundancy on the aircraft to provide acceptable flying qualities so that the pilot can still maintain control of the aircraft. Such an emphasis is understandable from the perspective that "loss of control" has been identified as a major cause of commercial aircraft hull losses. These research efforts need to be leveraged to provide a reliable means of assessing aircraft performance capability under any given damage scenario and autonomously adapting the flight control to achieve the desired performance.

Another area of technology development is that of autonomous control under adverse weather conditions. For current civil aircraft, the standard operational procedure is to disengage the autopilot during severe weather conditions because of ride quality and structural load/fatigue considerations. Technologies will need to be developed to have "smart" autopilots, which can maintain the desired control under adverse weather conditions without compromising aircraft structural integrity. The autonomous flight control will also need to have the capability to provide the integration with an autonomous propulsion system and adapt the flight control for changes in the propulsion system performance capability due to damage or the in-flight shut down of one or more engines due to safety considerations.

Autonomous Propulsion System

The propulsion system has to be considered separately from other aircraft subsystems, because the propulsion system is delivered as a "stand-alone" system and an aircraft might be certified for operation with engines supplied by more than one manufacturer. In the current airplanes, the pilot serves the critical function of integrating the propulsion system control with the flight control. The only exceptions to this are the "autothrottle" system, which is deployed as part of the autopilot and is limited to operation at cruise under fair weather conditions. Developing technologies for autonomous accomplishment of propulsion system control, diagnostics and prognostics functions is critical for enabling highly or fully autonomous operation of airplanes. For multi-engine aircraft, the most critical decision that the pilot makes regarding the propulsion system is whether or not to shut down an engine in flight based on any actual or perceived malfunctions, and then accommodate the affect of the lost propulsive capability through manipulation of available control effectors. The pilot uses many cues such as sound, vibration, smell etc. in addition to the information displayed via instruments monitoring the engine condition in making this decision. Sometimes the wrong decision is made as pointed out in the Boeing led study which identified “Propulsion System Malfunction Plus Inappropriate Crew Response” as one of the leading propulsion related causes of serious aircraft accidents. So at the very least, autonomous aircraft operation will require that the propulsion system be able to do “self-diagnostics” to determine its condition and be able to make an independent assessment whether it needs to be shut down to maintain the safety of the overall aircraft.

Also, the current propulsion systems are controlled and operated in a manner to not only maintain safe margins but also to have a high on-wing life in order to minimize maintenance costs. Such an approach, although desirable for nominal operations, might be extremely limiting when encountering off-nominal conditions. For instance, simulation studies for the Sioux City plane crash have shown that if the engine control could be modified to allow for higher thrust and thrust rates, the airplane could have been landed safely although the engines would have needed replacement. So in situations where the aircraft control surfaces are damaged, or additional control authority is needed from the propulsion system for other circumstances, it might be better to sacrifice engine life to ensure safety of the aircraft. To enable this capability, technologies will have to be developed to reliably predict engine life and performance capability under different operating scenarios and adjust the engine control based on the desired life/performance trade-off.

The Airspace Operation Challenges

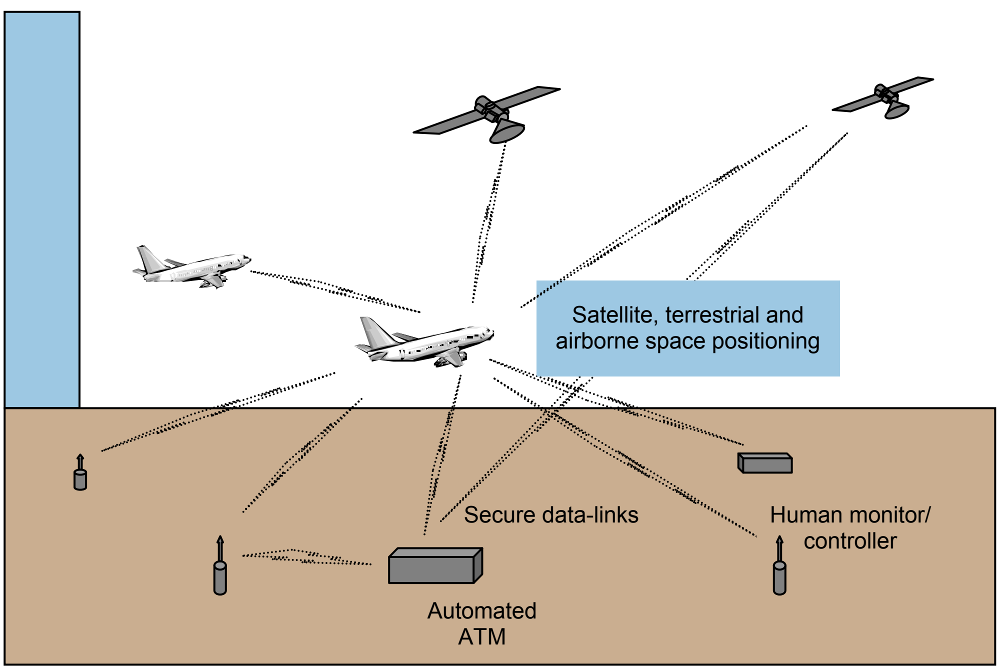
A multi-agency Joint Planning and Development Office (JPDO) was established in 2003 to develop the Next Generation Air Transportation System (NGATS) to meets the nation’s needs for 2020 and beyond. The primary focus is providing adequate system capacity, security and with minimal environmental impact. Research supporting the NGATS plan is considering additional automation but not specifically autonomous civil aircraft and operations as discussed here. To enable autonomous civil aircraft, the air traffic management research community will need to investigate infrastructures that could support, even stimulate, the most optimistic desired futuristic scenarios, and then define an infrastructure that is robust, adaptable and scaleable from the minimum to the most optimistic futures. The actual infrastructure would evolve only to the degree actually needed at any point in time. The future infrastructure should be capable of supporting autonomous aircraft operations from taxiing, takeoff, the entire flight path, landing, and ground operations under VFR and IFR conditions. It should be capable of supporting IFR operations from all airports, heliports and virtually any desired location, such as emergency medical evacuation helicopters operating from any street to a hospital, or autonomous cargo aircraft operating in and out of industrial parks, or automated personal air vehicles operating from any street. It should support automated ATM to varying degrees appropriate for national and international needs.

Functionality of the infrastructure must be robust. The system should be flexible, adaptable to change and tolerant to human and system errors. It must have sufficient reliability and availability to essentially never lose safety-critical functionality and, if possible, should enable relatively low-cost aircraft equipage. “Safety-critical functionality” means any function, such as precise aircraft location, velocity and orientation relative to the ground or another aircraft that is critical to controlling an aircraft or managing air traffic safely. Loss of that function puts at risk the aircraft and/or human life.

An integrated design approach is needed for the safety-critical infrastructure, including communications, space positioning, and ATM processing systems. Integrated design does not mean that all systems will be integrated into one single system. In fact, use of independent dissimilar redundancy should be one of the design options. It means that the total system requirements and all assets potentially available to support those requirements are considered in design alternatives. A driving requirement is for full functional availability in all but extremely rare situations even with multiple failures, which means multi-fail operational reliability. The design philosophy suggested for considering alternatives for the safety-critical infrastructure is similar to that for aircraft fly-by-wire flight control systems. Design options should not be limited to existing system capabilities. For example, if new capabilities are needed for GPS, Galileo and/or new space-based and ground-based augmentation systems, they can be proposed for future system upgrades.

Communication

Systems are needed to support multiple communication requirements with different levels of criticality, which are best served by independent networks. System-wide safety-critical information, such as aircraft space positioning information for precise guidance and ATM separation information, must be secure and highly reliable requiring multiple levels of redundancy. This also applies to aircraft-to-aircraft data-links used for close proximity operations and separation assurance. Air-to-air and ground-to-air data-links for the autonomous aircraft operations monitoring and backup control must have similarly high reliability. Weather information that could affect safety should be included in this network. Safety can be improved by providing safety-critical functionality from multiple dissimilar sources as indicated in the above figure. Security of these communications will be critical to ensure that command of the aircraft does not pass into the "wrong hands", or that spurious information is not communicated either from the aircraft to the ATM system and vice versa. Additionally security of communications within the aircraft will be critical to reliable and safe operation of the vehicle. Information needed for mission-critical but not safety-critical functions will need to be provided over a second independent network. This would include such items as flight path navigation, non-flight-critical weather information, airline operation center (AOC) mission information, and collaborative decision making information shared among AOCs, aircraft operators and ATM centers.



Communications Network for Autonomous Aircraft Flight in National Airspace

Space Positioning

Information used for precise guidance, landing and separation assurance is flight critical and must be extremely reliable. GPS is becoming a standard for the U.S. and Europe is developing Galileo as their primary space positioning system for aviation. UAVs currently use GPS for automated operations for military missions and a few civil applications. However, a single source for safety-critical functions supporting very large numbers of autonomous aircraft in civil airspace, as discussed above, would probably not provide adequate safety. Multiple independent systems using satellites, terrestrial and airborne sensors/systems will need to be considered. An integrated design approach for multi-fail operational capability with no loss of functionality will be needed for the space positioning information system.

Air Traffic Management

ATM information, processing and procedures in a fully automated ATM system becomes safety-critical. The architectural characteristics for these elements are highly dependent on the operational concept and airspace management approach defined to enable automated ATM. The operational concept must cover all types and categories of aircraft and modes of operation, from autonomous cargo and personal aircraft to very large passenger airliners and space transportation vehicles operating in civil airspace. The safety-critical information needed for automated ATM should come from the safety-critical secure communications network or networks. The sensing and processing systems are safety-critical and must provide full service functionality under all but extremely rare circumstances. Airports, heliports and any new types of takeoff and landing sites must be capable of supporting autonomous operations, including automatic take-off, landing and ground operations.

The Roadmap for Autonomous Civil Aircraft

Aviation, the safest form of long-distance transportation, is dependent on human operators in the aircraft and air traffic control. Most often when automation has been added, it has been human-centric, relying on humans as the decision maker and ultimate authority for assuring safety. A notable exception was the introduction of fly-by-wire systems where there are no mechanical backup modes for human control. The traveling public is generally unaware of the degree to which automation is used in air transportation. There was little public concern when crews were reduced from three to two and seemingly no concern about some air taxis flying with only one pilot.

The first step to both increasing human acceptance of autonomous aircraft, and gaining confidence in such operations, might be to have autonomous surveillance aircraft, such as for border patrol, forest fire detection etc., flying in limited air space. The next logical step will be to have autonomous cargo aircraft flying over water, such as cross Atlantic flights, taking off and landing at airports where there is no passenger traffic. These flights over a sustained period of time can be used to determine the robustness and reliability of the air traffic system, the autonomy system on board the aircraft and the capability to provide “one human operator monitoring multiple aircraft” capability. Once enough confidence has been gained in such operation, and safety records comparable to those of piloted aircraft have been established, small air taxi services for short duration flights can be offered on autonomous civil aircraft with a specially trained crew member on board to provide the steward services as well as alert the human operator monitoring the overall autonomous system of any unusual circumstances which need to be taken into account.

Large commercial passenger transport aircraft, as we know them today, will probably be the last one to achieve autonomous status, if ever. Although it is quite foreseeable that the autonomy technologies developed via the elements described earlier may enable operations of the large passenger aircraft with only one pilot on board. Whether we ever achieve this milestone or not, it is important to remember that “flying is fun” and any overall system that enables operation of autonomous civil aircraft has to allow enough flexibility for the enthusiast to pilot their own aircraft without any more restrictions being placed on them.

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Herman A. Rediess, National Institute of Aerospace, 100 Exploration Way, Hampton, Virginia 23666; and Sanjay Garg, Glenn Research Center. Responsible person, Sanjay Garg, organization code RIC, 216–433–2685.

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