Testimony of

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before the

Committee on Science, Space, and Technology
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Chairman Smith, Ranking Member Johnson, and members of the committee:

Thank you for the opportunity to appear before you today in my capacity as the Co-Chair the National Research Council's Committee on Autonomy Research for Civil Aviation. Together with my Co-Chair, John-Paul Clarke of the Georgia Institute of Technology, I had the pleasure of working with a distinguished group of scientists and engineers from a variety of disciplines and academic, industrial and government settings to develop a *national* research agenda to support the introduction of what we termed *increasingly autonomous* elements into our civil aviation system. This study was conducted at the request of NASA's Aeronautics Research Mission Directorate, and it was conducted over the course of about 18 months; our final report was issued last summer. Whereas our study was requested by NASA, we were asked not to provide recommendations to that one agency but moreover to identify and prioritize elements of a national agenda of research and development that could be pursued by government, academia, and industry. You have copies of the Summary of our report before you, and I will try to succinctly summarize our findings and recommendations below.

Before we get into the details of our findings, I want to summarize briefly the approach we took to this task. Because of our specific focus on civil aviation applications of increasingly autonomous systems, it was necessary to explicitly recognize a couple key characteristics of civil aviation that would set the context for our findings. First and foremost, one hallmark of our nation's civil aviation system is safety, especially in civil air transport operations. For a variety of reasons many decades in the making, our air transportation system operates at unprecedented levels of safety, and it is clear that the introduction of increasingly autonomous capabilities into that system will be acceptable only if they preserve or enhance this high level of safety and reliability. Secondly, we had to recognize the diversity of aircraft, ground systems, and personnel that comprise our civil aviation system. Because so-called "legacy" aircraft and support systems will continue to operate for the foreseeable future, it is clear that civil airspace must safely and efficiently accommodate everything from Piper J-3 Cubs designed in the 1930s to increasingly autonomous, unmanned rotary and fixed-wing vehicles whose designs and applications are continually evolving. These features and characteristics of civil aviation in the United States were key drivers of the elements of the national research agenda we recommended.

It is also important to understand how autonomous capabilities will be integrated over time into the National Airspace System (NAS). Our committee adopted the view that the civil aviation system of the future will evolve over time starting with a baseline defined by today's system, particularly with regard to levels of automation that are designed into present-day cockpits and air traffic management systems. *Autonomy*, in this context, is a characteristic or feature of future aviation automation systems that we use to refer to aviation systems that will be capable of *operations over extended distances and for long periods of time* ***without direct human supervision or intervention.*** As we point out in our report, this has some profound implications for urgent research in machine vision, perception, and cognition that must be developed to provide the functional equivalent of a "see-and-avoid" capability, which is the cornerstone for collision avoidance in our national aviation system. This is one key example of what we mean when we talk of *increasingly* autonomous systems—systems that will evolve to perform more and more of the functions presently provided by human pilots, controllers, and other skilled aviation personnel.

We started our task by identifying barriers to the increased use of autonomy in civil aviation systems and aircraft. Some of these barriers are technical, some are related to certification and regulation, and some are related to legal and social concerns. Our research agenda was developed to address these barriers.

The *Technology Barriers* we identified are as follows: (1) *Communications and data acquisition* requirements in an increasingly autonomous civil aviation system may push the boundaries of bandwidth and spectrum management necessary to support these operations; (2) *Cyberphysical security*, a topic of increasing concern generally, may be particularly critical to ensure the stability, reliability and functionality of the increasingly-autonomous civil aviation system of the future; (3) *Decision-making by adaptive, non-deterministic systems* is a critical element of autonomy in civil aviation systems, and there are significant challenges to the design, implementation and testing of such systems at present; (4) As I've previously mentioned, the *diversity of vehicles and systems* that must be accommodated in a civil aviation system will make it more difficult to incorporate increasingly autonomous systems; (5) advances in *human-machine integration* are needed because increasingly autonomous systems will require humans and machines to work together in new and different ways that have not yet been identified. (6) I've also mentioned machine *sensing, perception, and cognition* as a significant technological hurdle that must be addressed; (7) Increasingly autonomous systems will present new, and not well-understood challenges in terms of *system complexity* and the ability of the civil aviation system as a whole to resist precipitous declines in performance because of isolated failures in one part of the system; and finally, (8) Existing approaches to the formal *verification and validation* of systems are not adequate to address these requirements in increasingly autonomous systems. Each of these technical barriers is more fully-developed in the text of our report.

Four barriers in our report are related to *Regulation and Certification*: (1) *Airspace access for unmanned aircraft* is a significant barrier for present operations of unmanned aircraft; (2) Today's *certification process* doesn't adequately take into account the special characteristics of increasingly autonomous systems; (3) Many of the safety standards and requirements that are applied to increasingly autonomous systems were developed in the context of crewed, passenger-carrying aircraft, and it's not clear how well-suited they are to assure an *equivalent level of safety* for unmanned aircraft operations; and (4) Even if we had adequate processes and procedures for verification, validation, and certification of increasingly autonomous systems, the absence of *trust* in such systems will impose significant barriers to their widespread adoption and utilization.

Finally, our committee identified two other barriers that could seriously impede the degree and speed of adoption of increasingly autonomous technology in civil aviation: These are (1) *legal issues* associated with public policy, law. and regulation, and (2) *social issues*, especially public concerns about privacy and safety.

From a consideration of these technical, regulatory/certification, and social/legal barriers, our committee identified eight high-level research projects that collectively will enable the realization of our vision of increasingly autonomous civil aviation systems and operations. Our report discusses each of these in some depth, but in the interest of time this afternoon, I'll simply summarize and highlight our recommendations for a national research agenda. I would also point out that the committee feels that each of these research issues is important, but we consider the first four of these to be most urgent and most difficult.

1. **Behavior of Adaptive/Nondeterministic Systems:** Autonomous systems are characterized by their ability to learn from experience and to adapt to changing conditions. This means that the outputs of such systems can change over time, and that their response to a given set of conditions might be different over time as the systems gain experience. This poses significant technical challenges for design, testing and certification of these systems.

2. **Operation Without Continuous Human Oversight:** Another defining characteristic of increasingly autonomous systems is their ability to operate for extended periods of time without direct human oversight, that is, without the need for a human to monitor, supervise, and/or directly intervene in the operation of these systems in real time. This will require that the functions currently provided by human operators are accomplished by the increasingly autonomous systems during periods when the system operates unattended. Increasingly autonomous systems will need to respond safely to degradation or failure of aircraft systems as well as other high-risk situations encountered during a mission.

3. **Modeling and Simulation:** The committee recommends a significant undertaking to develop the theoretical basis and methodologies for using modeling and simulation to accelerate the development and maturation of increasingly autonomous systems and aircraft. Potential applications include component design, training and coaching of human operators, creating and enhancing human trust in increasingly autonomous systems, accident and incident investigation, and furthering our understanding of cybersecurity vulnerabilities and how to mitigate those risks.

4. **Verification, Validation, and Certification:** I've previously stated our committee's concerns about the inadequacy of present approaches to verification, validation, and certification of increasingly autonomous systems. It is important to recognize, however, that one of the key reasons for the previously-noted high levels of safety we experience

in civil aviation is because of the formal requirements imposed by the FAA for verification, validation, and/or certification of hardware, software and people, as appropriate.

5. **Nontraditional Methodologies and Technologies:** The active and growing community of hobbyists and prospective entrepreneurs developing increasingly autonomous unmanned aircraft and associated systems are relying heavily on open-source hardware and software, resulting in a proliferation of low-cost, highly-capable technology. We believe that such technologies will be a key element of the increasingly autonomous civil aviation system of the future, and urge research and development that will allow these technologies to be used safely and efficiently. This would include, in our view, the research that would allow the use of open-source intelligent software in safety-critical applications, including unlimited flight operations.

6. **Roles of Personnel and Systems:** There may be a tendency to believe that the advent of increasingly autonomous systems will lessen the need to assure proper consideration of human factors in the engineering of such systems. However, our committee believes quite the opposite. Because intelligent, adaptive/non-deterministic systems will require humans and machines to work together in previously unanticipated ways, it is imperative that research be undertaken to further understand the roles and responsibilities of humans and machines, and to address the question of how to safely and efficiently integrate these in an operational environment.

7. **Safety and Efficiency:** The committee believes that increasingly autonomous systems could enhance the safety and efficiency of civil aviation. Our report discusses a wide range of potential applications of increasingly autonomous technology that could greatly reduce the risk to humans involved in operations such as aerial fire-fighting operations. We also recognize that such technology might readily be applied to improve the safety of general aviation, especially with respect to single-pilot operations by, in effect, incorporating an "electronic co-pilot" that could provide needed, timely assistance to a human pilot. We recommend that this research project include an analysis of accidents and incidents to determine those instances where increasingly autonomous systems might have made a positive outcome possible. Such systems would not be susceptible to factors that adversely affect human performance, such as stress or fatigue. Effective development of increasingly autonomous systems could have a major impact on the need for highly-skilled, highly-trained people.

8. **Stakeholder Trust:** Increasingly autonomous systems can fundamentally change the relationship between people and technology, and one important dimension of that relationship is trust. Even if the necessary developments for verification, validation, and

certification are successfully accomplished, in the absence of trust, the potential benefits of increasingly autonomous systems cannot be realized. It is therefore necessary to understand what attributes of systems affect their trustworthiness and how this is communicated to the people who are responsible for their operation.

These then are the major recommendations for research developed by our committee. Although this study was done at the request of NASA's Aeronautics Research Mission Directorate, we were specifically directed to develop a national research agenda rather than a NASA research agenda. We thus recognize that the research we've recommended can and should be addressed by multiple organizations in the federal government, industry and academia. Clearly the FAA has a major role to play, particularly for those elements pertaining to verification, validation and certification. The Department of Defense, although primarily concerned with military applications of this technology, also has a requirement for at least some of their unmanned aircraft to be able to fit seamlessly into operations in the National Aviation System. Each of the high-priority research projects overlaps to some extent with one or more of the other projects, and each would be best addressed by multiple organizations working in concert. There is already some movement in that direction, however, we believe there is an ongoing need for active coordination of the research effort related to autonomy in civil aviation.

Civil aviation in the United States and elsewhere in the world is on the threshold of profound changes in the way it operates because of the rapid evolution of increasingly autonomous systems. Advanced systems will, among other things, be able to operate without direct human supervision or control for extended periods of time and over long distances. As happens with any other rapidly evolving technology, early adapters sometimes get caught up in the excitement of the moment, producing a form of intellectual hyperinflation that greatly exaggerates the promise of things to come and greatly underestimates costs in terms of money, time, and—in many cases—unintended consequences or complications. While there is little doubt that over the long run the potential benefits of increasingly autonomous systems in civil aviation will indeed be great, there should be equally little doubt that getting there, while maintaining or improving the safety and efficiency of U.S. civil aviation, will be no easy matter. Furthermore, given that the potential benefits of advanced systems—as well as the unintended consequences—will inevitably accrue to some stakeholders much more than others, the enthusiasm of the latter for fielding increasingly autonomous systems could be limited. In any case, overcoming the barriers identified in this report by pursuing the research agenda proposed by the committee is a vital next step. Even so, more work beyond the issues identified here will certainly be needed as the nation ventures into this new era of flight.

The Summary from our report is attached.

AUTONOMY RESEARCH FOR CIVIL AVIATION

TOWARD A NEW ERA OF FLIGHT

REPORT SUMMARY

Committee on Autonomy Research for Civil Aviation

Aeronautics and Space Engineering Board

Division on Engineering and Physical Sciences

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Summary

The development and application of increasingly autonomous (IA) systems for civil aviation (see Boxes S.1 and S.2) are proceeding at an accelerating pace, driven by the expectation that such systems will return significant benefits in terms of safety, reliability, efficiency, affordability, and/or previously unattainable mission capabilities. IA systems, characterized by their ability to perform more complex mission-related tasks with substantially less human intervention for more extended periods of time, sometimes at remote distances, are being envisioned for aircraft and for air traffic management (ATM) and other ground-based elements of the National Airspace System (NAS) (see Box S.3). This vision and the associated technological developments have been spurred in large part by the convergence of the increased availability of low-cost, highly capable computing systems; sensor technologies; digital communications systems; precise position, navigation, and timing information (e.g., from the Global Positioning System (GPS); and open-source hardware and software.

These technology enablers, coupled with expanded use of IA systems in military operations and the emergence of an active and growing community of hobbyists that is developing and operating small unmanned aircraft systems (UAS), provide fertile ground for innovation and entrepreneurship (see Box S.4). The burgeoning industrial sector devoted to the design, manufacture, and sales of IA systems is indicative of the perceived economic opportunities that will arise. In short, civil aviation is on the threshold of potentially revolutionary changes in aviation capabilities and operations associated with IA systems. These systems, however, pose serious unanswered questions about how to safely integrate these revolutionary technological advances into a well-established, safe, and efficiently functioning NAS governed by operating rules that can only be changed after extensive deliberation and consensus. In addition, the potential benefits that could accrue from the introduction of advanced IA systems in civil aviation, the associated costs, and the unintended consequences that are likely to arise will not fall on all stakeholders equally. This report suggests major elements of a national research agenda for autonomy in civil aviation that would inform and support the orderly implementation of IA systems in U.S. civil aviation. The scope of this study does not include organizational recommendations.

BARRIERS TO INCREASED AUTONOMY IN CIVIL AVIATION

The Committee on Autonomy Research for Civil Aviation has identified many substantial barriers to the increased use of autonomy in civil aviation systems and aircraft. These barriers cover a wide range of issues related

BOX S.1
Civil Aviation

In this report, "civil aviation" is used to refer to all nonmilitary aircraft operations in U.S. civil airspace. This includes operations of civil aircraft as well as nonmilitary public use aircraft (that is, aircraft owned or operated by federal, state, and local government agencies other than the Department of Defense). In addition, many of the IA technologies that would be developed by the recommended research projects would generally be applicable to military crewed and/or unmanned aircraft for military operations and/or other operations in the NAS.

BOX S.2
Increasingly Autonomous Systems

A fully autonomous aircraft would not require a pilot; it would be able to operate independently within civil airspace, interacting with air traffic controllers and other pilots just as if a human pilot were on board and in command. Similarly, a fully autonomous ATM system would not require human air traffic controllers. This study is not focused on these extremes (although it does sometimes address the needs or qualities of fully autonomous unmanned aircraft). Rather, the report primarily addresses what the committee calls "increasingly autonomous" (IA) systems, which lie along the spectrum of system capabilities that begin with the abilities of current automatic systems, such as autopiloted and remotely piloted (nonautonomous) unmanned aircraft, and progress toward the highly sophisticated systems that would be needed to enable the extreme cases. Some IA systems, particularly adaptive/nondeterministic IA systems, lie farther along this spectrum than others, and in this report such systems are typically described as "advanced IA systems."

BOX S.3
National Airspace System

The NAS is "the common network of U.S. airspace; air navigation facilities, equipment, and services; airports or landing areas; aeronautical charts, information and services; rules, regulations, and procedures; technical information; and manpower and material" (Integration of Civil Unmanned Aircraft Systems [UAS] in the National Airspace System [NAS] Roadmap, FAA, 2013). Some NAS facilities are jointly operated by the FAA and the Department of Defense. IA systems could be incorporated into airport ground systems such as snow plows. However, the greatest technological, social, and legal challenges to the use of IA systems in civil aviation are associated with their use in aircraft and air traffic management systems, and the report does not specifically address the use of IA systems in airport ground systems.

BOX S.4
Unmanned Aircraft/Crewed Aircraft

An unmanned aircraft is "a device used or intended to be used for flight in the air that has no onboard pilot. This device excludes missiles, weapons, or exploding warheads, but includes all classes of airplanes, helicopters, airships, and powered-lift aircraft without an onboard pilot. Unmanned aircraft do not include traditional balloons (see 14 CFR Part 101), rockets, tethered aircraft and un-powered gliders." A UAS is "an unmanned aircraft and its associated elements related to safe operations, which may include control stations (ground-, ship-, or air-based), control links, support equipment, payloads, flight termination systems, and launch/recovery equipment" (Integration of Civil Unmanned Aircraft Systems [UAS] in the National Airspace System [NAS] Roadmap, Federal Aviation Administration [FAA], 2013). UAS include the data links and other communications systems used to connect the UAS control station, unmanned aircraft, and other elements of the NAS, such as ATM systems and human operators. Unless otherwise specified, UAS are assumed to have no humans on board either as flight crew or as passengers. "Crewed aircraft" is used to denote manned aircraft; unless specifically noted otherwise; manned aircraft are considered to have a pilot on board.

to understanding, developing, and deploying IA ground and aircraft systems. Some of these issues are technical, some are related to certification and regulation, and some are related to legal and social concerns.

- Technology barriers
  —*Communications and data acquisition.* Civil aviation wireless communications are fundamentally limited in bandwidth, and the operation of unmanned aircraft in the NAS could substantially increase the demand for bandwidth.
  —*Cyberphysical security.* The use of increasingly interconnected networks and increasingly complex software embedded throughout IA air- and ground-based system elements, as well as the increasing sophistication of potential cyberphysical attacks, threaten the safety and reliability of IA systems.
  —*Decision making by adaptive/nondeterministic systems* (see Box S.5). The lack of generally accepted design, implementation, and test practices for adaptive/nondeterministic systems will impede the deployment of some advanced IA vehicles and systems in the NAS.
  —*Diversity of vehicles.* It will be difficult to engineer some IA systems so that they are backward-compatible with legacy airframes, ATM systems, and other elements of the NAS.
  —*Human–machine integration.* Incorporating IA systems and vehicles in the NAS would require humans and machines to work together in new and different ways that have not yet been identified.
  —*Sensing, perception, and cognition.* The ability of IA systems to operate independently of human operators (see Box S.6) is fundamentally limited by the capabilities of machine sensory, perceptual, and cognitive systems.
  —*System complexity and resilience.* IA capabilities create a more complex aviation system, with new interdependencies and new relationships among various operational elements. This will likely reduce the resilience of the NAS because disturbances in one portion of the system could, in certain circumstances, cause the performance of the entire system to degrade precipitously.
  —*Verification and validation (V&V).* Existing V&V approaches and methods are insufficient for advanced IA systems.
- Regulation and certification barriers
  —*Airspace access for unmanned aircraft.* Unmanned aircraft may not operate in nonsegregated civil airspace unless the Federal Aviation Administration (FAA) issues a certificate of waiver or authorization (COA).

BOX S.5
Adaptive/Nondeterministic Systems

Adaptive systems have the ability to modify their behavior in response to their external environment. For aircraft systems, this could include commands from the pilot and inputs from aircraft systems, including sensors that report conditions outside the aircraft. Some of these inputs, such as airspeed, will be stochastic because of sensor noise as well as the complex relationship between atmospheric conditions and sensor readings not fully captured in calibration equations. Adaptive systems learn from their experience, either operational or simulated, so that the response of the system to a given set of inputs varies and, presumably, improves over time.

Systems that are nondeterministic may or may not be adaptive. They may be subject to the stochastic influences imposed by their complex internal operational architectures or their external environment, meaning that they will not always respond in precisely the same way even when presented with identical inputs or stimuli. The software that is at the heart of nondeterministic systems is expected to enable improved performance because of its ability to manage and interact with complex "world models" (large and potentially distributed data sets) and execute sophisticated algorithms to perceive, decide, and act in real time.

Systems that are adaptive and nondeterministic demonstrate the performance enhancements of both. Many advanced IA systems are expected to be adaptive and/or nondeterministic, and issues associated with the development and deployment of these adaptive/nondeterministic systems are discussed later in the report.

BOX S.6
Operators

In this report, the term "operator" generally refers to pilots, air traffic controllers, airline flight operations staff, and other personnel who interact directly with IA civil aviation systems. "Pilot" is used when referring specifically to the operator of a crewed aircraft. With regard to unmanned aircraft, the FAA says that "in addition to the crewmembers identified in 14 CFR Part 1 [pilots, flight engineers, and flight navigators], a UAS flight crew includes pilots, sensor/payload operators, and visual observers, but may include other persons as appropriate or required to ensure safe operation of the aircraft" (Integration of Civil Unmanned Aircraft Systems [UAS] in the National Airspace System [NAS] Roadmap, FAA, 2013). Given that the makeup, certification requirements, and roles of UAS flight crews are likely to evolve as UAS acquire advanced IA capabilities, this report refers generally to UAS operators as flight crew rather than specifically as pilots.

—*Certification process.* Existing certification criteria, processes, and approaches do not take into account the special characteristics of advanced IA systems.
—*Equivalent level of safety.* Many existing safety standards and requirements, which are focused on assuring the safety of aircraft passengers and crew on a particular aircraft, are not well suited to assure the safety of unmanned aircraft operations, where the primary concern is the safety of personnel in other aircraft and on the ground.
—*Trust in adaptive/nondeterministic IA systems.* Verification, validation, and certification are necessary but not sufficient to engender stakeholder trust in advanced adaptive/nondeterministic IA systems.

- Other barriers
  —*Legal issues.* Public policy, as reflected in law and regulation, could significantly impede the degree and speed of adoption of IA technology in the NAS.
  —*Social issues.* Social issues, particularly public concerns about privacy and safety, could significantly impede the degree and speed of adoption of IA technology in the NAS.

The committee did not individually prioritize these barriers. However, there is one critical, crosscutting challenge that must be overcome to unleash the full potential of advanced IA systems in civil aviation. This challenge may be described in terms of a question: "How can we assure that advanced IA systems—especially those systems that rely on adaptive/nondeterministic software—will enhance rather than diminish the safety and reliability of the NAS?" There are four particularly challenging barriers that stand in the way of meeting this critical challenge:

- Certification process
- Decision making by adaptive/nondeterministic systems
- Trust in adaptive/nondeterministic IA systems
- Verification and validation

ELEMENTS OF A NATIONAL RESEARCH AGENDA FOR AUTONOMY IN CIVIL AVIATION

The committee identified eight high-level research projects that would address the barriers discussed above. The committee also identified several specific areas of research that could be included in each research project.

Recommendation. ***National Research Agenda.*** **Agencies and organizations in government, industry, and academia that are involved in research, development, manufacture, certification, and regulation of IA technologies and systems should execute a national research agenda in autonomy that includes the following high-priority research projects, with the first four being the most urgent and the most difficult:**

- ***Behavior of Adaptive/Nondeterministic Systems.*** **Develop methodologies to characterize and bound the behavior of adaptive/nondeterministic systems over their complete life cycle.**
- ***Operation Without Continuous Human Oversight.*** **Develop the system architectures and technologies that would enable increasingly sophisticated IA systems and unmanned aircraft to operate for extended periods of time without real-time human cognizance and control.**
- ***Modeling and Simulation.*** **Develop the theoretical basis and methodologies for using modeling and simulation to accelerate the development and maturation of advanced IA systems and aircraft.**
- ***Verification, Validation, and Certification.*** **Develop standards and processes for the verification, validation, and certification of IA systems, and determine their implications for design.**
- ***Nontraditional Methodologies and Technologies.*** **Develop methodologies for accepting technologies not traditionally used in civil aviation (e.g., open-source software and consumer electronic products) in IA systems.**
- ***Roles of Personnel and Systems.*** **Determine how the roles of key personnel and systems, as well as related human–machine interfaces, should evolve to enable the operation of advanced IA systems.**
- ***Safety and Efficiency.*** **Determine how IA systems could enhance the safety and efficiency of civil aviation.**
- ***Stakeholder Trust.*** **Develop processes to engender broad stakeholder trust in IA systems for civil aviation.**

FOUR MOST URGENT AND MOST DIFFICULT RESEARCH PROJECTS

Behavior of Adaptive/Nondeterministic Systems. Develop methodologies to characterize and bound the behavior of adaptive/nondeterministic systems over their complete life cycle.

Adaptive/nondeterministic properties will be integral to many advanced IA systems, but they will create challenges for assessing and setting the limits of their resulting behaviors. Advanced IA systems for civil aviation operate in an uncertain environment where physical disturbances, such as wind gusts, are often modeled using probabilistic models. These IA systems may rely on distributed sensor systems that have noise with stochastic properties such as uncertain biases and random drifts over time and varying environmental conditions. To improve performance, adaptive/nondeterministic IA systems will take advantage of evolving conditions and past experience to adapt their behavior; that is, they will be capable of learning. As these IA systems take over more functions traditionally performed by humans, there will be a growing need to incorporate autonomous monitoring and other safeguards to ensure continued appropriate operational behavior.

There is tension between the benefits of incorporating software with adaptive/nondeterministic properties in IA systems and the requirement to test such software for safe and assured operation. Research is needed to develop new methods and tools to address the inherent uncertainties in airspace system operations and thereby enable more complex adaptive/nondeterministic IA systems with the ability to adapt over time to improve their performance and provide greater assurance of safety.

Specific tasks to be carried out by this research project include the following:

- Develop mathematical models for describing adaptive/nondeterministic processes as applied to humans and machines.
- Develop performance criteria, such as stability, robustness, and resilience, for the analysis and synthesis of adaptive/nondeterministic behaviors.
- Develop methodologies beyond input-output testing for characterizing the behavior of IA systems.
- Determine the roles that humans play in limiting the behavior of adaptive/nondeterministic systems and how IA systems can take over those roles.

Operation Without Continuous Human Oversight. Develop the system architectures and technologies that would enable increasingly sophisticated IA systems and unmanned aircraft to operate for extended periods of time without real-time human cognizance and control.

Crewed aircraft have systems with varying levels of automation that operate without continuous human oversight. Even so, pilots are expected to maintain continuous cognizance and control over the aircraft as a whole. Advanced IA systems could allow unmanned aircraft to operate for extended periods of time without the need for human operators to monitor, supervise, and/or directly intervene in the operation of those systems in real time. This will require that certain critical system functions currently provided by humans, such as “detect and avoid,” performance monitoring, subsystem anomaly and failure detection, and contingency decision making, are accomplished by the IA systems during periods when the system operates unattended. Eliminating the need for continuous cognizance and control of unmanned aircraft operations would enable unmanned aircraft to take on new roles that are not practical or cost-effective with continuous oversight. This capability could also improve the safety of crewed operations in situations where risk to a human operator is unacceptably high, workload is too heavy, or the task too monotonous to expect continuous operator vigilance.

Successful development of an unattended operational capability depends on understanding how humans perform their roles in the present system and how these roles are translated to the IA system, particularly for high-risk situations. Eliminating the need for continuous human oversight requires a system architecture that also supports intermittent human cognizance and control.

Specific tasks to be carried out by this research project include the following:

- Investigate human roles, including temporal requirements for supervision, as a function of the mission, capabilities, and limitations of IA systems.
- Develop IA systems that respond safely to the degradation or failure of aircraft systems.
- Develop IA systems to identify and mitigate high-risk situations induced by the mission, the environment, or other elements of the NAS.
- Develop detect-and-avoid IA systems that do not need continuous human oversight.
- Investigate airspace structures that could support UAS operations in confined or pre-approved operating areas using methods such as geofencing.

Modeling and Simulation. Develop the theoretical basis and methodologies for using modeling and simulation to accelerate the development and maturation of advanced IA systems and aircraft.

Modeling and simulation capabilities will play an important role in the development, implementation, and evolution of IA systems in civil aviation because they provide researchers, designers, regulators, and operators with insights into component and system performance without necessarily engendering the expense and risk associated with actual operations. For example, computer simulations may be able to test the performance of some IA systems in literally millions of scenarios in a short time to produce a statistical basis for determining safety risks and establishing the confidence of IA system performance. Researchers and designers are also likely to make use of modeling and simulation capabilities to evaluate design alternatives. Developers of IA systems will be able to train adaptive (i.e., learning) algorithms through repeated operations in simulation. Modeling and simulation capabilities could also be used to train human operators. The committee envisions the creation of a distributed suite of modeling and simulation modules developed by disparate organizations with the ability to be interconnected or networked, as appropriate, based on established standards. The committee believes that monolithic modeling and simulation efforts that are intended to develop capabilities that can "do it all" and answer any and all questions tend to be ineffective due to limitations in access and availability; the higher cost of creating, employing, and maintaining them; the complexity of their application, which constrains their use; and the centralization of development risks. Given the importance of modeling and simulation capabilities to the creation, evaluation, and evolution of IA systems, mechanisms will be needed to ensure that these capabilities perform as intended. A process for accrediting models and simulations will also be required.

Specific tasks to be carried out by this research project include the following:

- Develop theories and methodologies that will enable modeling and simulation to serve as embedded components within adaptive/nondeterministic systems.
- Develop theories and methodologies for using modeling and simulation to coach adaptive IA systems and human operators during training exercises.
- Develop theories and methodologies for using modeling and simulation to create trust and confidence in the performance of IA systems.
- Develop theories and methodologies for using modeling and simulation to assist with accident and incident investigations associated with IA systems.
- Develop theories and methodologies for using modeling and simulation to assess the robustness and resiliency of IA systems to intentional and unintentional cybersecurity vulnerabilities.
- Develop theories and methodologies for using modeling and simulation to perform comparative safety risk analyses of IA systems.
- Create and regularly update standardized interfaces and processes for developing modeling and simulation components for eventual integration.
- Develop standardized modules for common elements of the future system, such as aircraft performance, airspace, environmental circumstances, and human performance.
- Develop standards and methodologies for accrediting IA models and simulations.

Verification, Validation, and Certification. Develop standards and processes for the verification, validation, and certification of IA systems and determine their implications for design.

The high levels of safety achieved in the operation of the NAS largely reflect the formal requirements imposed by the FAA for verification, validation, and certification (VV&C) of hardware and software and the certification of personnel as a condition for entry into the system. These processes have evolved over many decades and represent the cumulative experience of all elements of civil aviation—manufacturers, regulators, pilots, controllers, other operators—in the operation of that system. Although viewed by some as unnecessarily cumbersome and expensive, VV&C processes are critical to the continued safe operation of the NAS. However, extension of these concepts and principles to advanced IA systems is not a simple matter and will require the development of new approaches and tools. Furthermore, the broad range of aircraft sizes, masses, and capabilities envisioned in future civil aviation operations may present opportunities to reassess the current safety and reliability criteria for various components of the aviation system. As was done in the past during the introduction of major new technologies, such as fly-by-wire flight control system and composite materials, the FAA will need to develop technical competency in IA systems and issue guidance material and new regulations to enable safe operation of all classes and types of IA systems.

Specific tasks to be carried out by this research project include the following:

- Characterize and define requirements for intelligent software and systems.
- Improve the fidelity of the VV&C test environment.
- Develop, assess, and propose new certification standards.
- Define new design requirements and methodologies for IA systems.
- Understand the impact that airspace system complexity has on IA system design and on VV&C.
- Develop VV&C methods for products created using nontraditional methodologies and technologies.

ADDITIONAL HIGH-PRIORITY RESEARCH PROJECTS

Nontraditional Methodologies and Technologies. Develop methodologies for accepting technologies not traditionally used in civil aviation (e.g., open-source software and consumer electronic products) in IA systems.

Open-source hardware and software are being widely used in the rapidly evolving universe of IA systems. This is particularly, but not uniquely, true in the active and growing community of hobbyists and prospective entrepreneurs who are developing and operating small unmanned aircraft. Separately, the automotive industry is deploying IA systems using V&V methods different from the methods traditionally used in aviation. The committee believes that there are many potential safety and economic benefits that might be realized in the civil aviation environment by developing suitable methodology that would permit reliable, safe adoption of hardware and software systems of unknown provenance. Although these issues are closely related to issues of V&V and certification, the committee believes they merit independent research attention. This might open up new opportunities for the beneficial deployment of technologies that fall outside traditional uses and applications.

Specific tasks to be carried out by this research project include the following:

- Develop modular architectures and protocols that support the use of open-source products for non-safety-critical applications.
- Develop and mature nontraditional software languages for IA applications.
- Develop paths for migrating open-source, intelligent software to safety-critical applications and unrestricted flight operations.
- Define new operational categories that would enable or accelerate experimentation, flight testing, and deployment of nontraditional technologies.

The final phase of this research project would be accomplished by the VV&C research project as it develops certification standards.

Roles of Personnel and Systems. Determine how the roles of key personnel and systems, as well as related human–machine interfaces, should evolve to enable the operation of IA systems.

Effectively integrating humans and machines in the civil aviation system has been a high priority and sometimes an elusive design challenge for decades. Human–machine integration may become an even greater challenge with the advent of advanced IA systems. Although the reliance on high levels of automation in crewed aircraft has increased the overall levels of system safety, persistent and seemingly intractable issues arise in the context of incidents and accidents. Typically, pilots experience difficulty in developing and maintaining an appropriate mental model of what the automation is doing at any given time. Maintaining an awareness of the operational mode of key automated systems can become especially problematic in dynamic situations. Advanced IA systems will change the specifics of the human performance required by such systems, but it remains to be seen if cognitive requirements for human operators will be more or less stringent. Not only are there significant issues surrounding the proper roles and responsibilities of humans in such systems, but there are also important new questions about the properties and characteristics of the human–machine interface posed by the adaptive/nondeterministic behavior of these systems. The committee believes that in many ways, these are a logical extension of the age-old questions about duties, responsibilities, and skills and training required for pilots, air traffic controllers, and other humans in the system. However, advanced IA systems may permit, or even require, new roles and radical realignment of the more traditional roles of such human actors to achieve some of the benefits envisioned. The importance of these issues cannot be overstated, and, again, realization of projected benefits of autonomy will be constrained by failure to address the issues through research.

Specific tasks to be carried out by this research project include the following:

- Develop human–machine interface tools and methodologies to support operation of advanced IA systems during normal and atypical operations.
- Develop tools and methodologies to ensure effective communication among IA systems and other elements of the NAS.
- Define the rationale and criteria for assigning roles to key personnel and IA systems and assessing their ability to perform those roles under realistic operating conditions.
- Develop intuitive human–machine integration technologies to support real-time decision making, particularly in high-stress, dynamic situations.
- Develop methods and technologies to enable situational awareness that supports the integration of IA systems.

Safety and Efficiency. Determine how IA systems could enhance the safety and efficiency of the civil aviation system.

As with other new technologies, poorly implemented IA systems could put at risk the high levels of efficiency and safety that are the hallmarks of civil aviation, particularly for commercial air transportation. However, done properly, advances in IA systems could enhance both the safety and the efficiency. For example, IA systems have the potential to reduce reaction times in safety-critical situations, especially in circumstances that today are encumbered by the requirement for human-to-human interactions. The ability of IA capabilities to rapidly cue operators or potentially render a fully autonomous response in safety-critical situations could improve both safety and efficiency. IA systems could substantially reduce the frequency of those classes of accidents typically ascribed to operator error. This could be of particular value in the segments of civil aviation, such as general aviation and medical evacuation helicopters, that have much higher accident rates than commercial air transports.

Whether located on board an aircraft or in ATM centers, IA systems also have the potential to reduce manpower requirements, thereby increasing the efficiency of operations and reducing operating costs.

In instances where IA systems make it possible for small unmanned aircraft to replace crewed aircraft, the risks to persons and property on the ground in the event of an accident could be greatly reduced, owing to the reduced damage footprint in those instances, and the risk to air crew is eliminated entirely.

Specific tasks to be carried out by this research project include the following:

- Analyze accident and incident records to determine where IA systems may have prevented or mitigated the severity of specific accidents or classes of accidents.
- Develop and analytically test methodologies to determine how the introduction of IA systems in flight operations, ramp operations by aircraft and ground support equipment, ATM systems, airline operation control centers, and so on might improve safety and efficiency.
- Investigate airspace structures and operating procedures to ensure safe and efficient operations of legacy and IA systems in the NAS.

Stakeholder Trust. Develop processes to engender broad stakeholder trust in IA systems in the civil aviation system.

IA systems can fundamentally change the relationship between people and technology, and one important dimension of that relationship is trust. Although increasingly used as an engineering term in the context of software and security assurance, trust is above all a social term and becomes increasingly relevant to human–technology relationships when complexity thwarts the ability to fully understand a technology's behavior. Trust is not a trait of the system; it is the system status in the mind of human beings based on their perception of and experience with the system. Trust concerns the attitude that a person or technology will help achieve specific goals in a situation characterized by uncertainty and vulnerability.[1] It is the perception of trustworthiness that influences how people respond to a system.

Although closely related to VV&C, trust warrants attention as a distinct research topic because formal certification does not guarantee trust and eventual adoption. Stakeholder trust is also tied to cybersecurity and related issues; trustworthiness depends on the intent of designers and on the degree to which the design prevents both inadvertent and intentional corruption of system data and processes.

Specific tasks to be carried out by this research project include the following:

- Identify the objective attributes of trustworthiness and develop measures of trust that can be tailored to a range of applications, circumstances, and relevant stakeholders.
- Develop a systematic methodology for introducing IA system functionality that matches authority and responsibility with earned levels of trust.
- Determine the way in which trust-related information is communicated.
- Develop approaches for establishing trust in IA systems.

COORDINATION OF RESEARCH AND DEVELOPMENT

All of the research projects described above can and should be addressed by multiple organizations in the federal government, industry, and academia.

The roles of academia and industry would be essentially the same for each research project because of the nature of the role that academia and industry play in the development of new technologies and products.

The FAA would be most directly engaged in the VV&C research project, because certification of civil aviation systems is one of its core functions. However, the subject matters of most of the other research projects are also related to certification directly or indirectly, so the FAA would be ultimately be interested in the progress and results of those other projects as well.

The Department of Defense (DOD) is primarily concerned with military applications of IA systems, though it must also ensure that military aircraft with IA systems that are based in the United States satisfy requirements for operating in the NAS. Its interests and research capabilities coincide with all eight research projects, especially with those on the roles of personnel and systems and operation without continuous human oversight.

[1] J.D. Lee and K.A. See, 2004, Trust in automation: Designing for appropriate reliance, *Human Factors* 46(1): 50-80.

NASA supports basic and applied research in civil aviation technologies, including ATM technologies of interest to the FAA. Its interests and research capabilities also encompass the scope of all eight research projects, particularly modeling and simulation, nontraditional methodologies and technologies, and safety and efficiency.

Each of the high-priority research projects overlaps to some extent with one or more of the other projects, and each would be best addressed by multiple organizations working in concert. There is already some movement in that direction.

The FAA has created the Unmanned Aircraft Systems Integration Office to foster collaboration with a broad spectrum of stakeholders, including DOD, NASA, industry, academia, and technical standards organizations. In 2015, the FAA will establish an air transportation center of excellence for UAS research, engineering, and development. In addition, the NextGen Joint Planning and Development Office (JPDO), which is executing a multiagency research and development plan to improve the NAS, has issued a roadmap for UAS research, development, and demonstration.[2] Efforts such as these are necessary and could be strengthened to assure that the full scope of IA research and development efforts (not just those focused on UAS applications) is effectively coordinated and integrated, with minimal duplication of research and without critical gaps. In particular, more effective coordination among relevant organizations in government, academia, and industry would help execute the recommended research projects more efficiently, in part by allowing lessons learned from the development, test, and operation of IA systems to be continuously applied to ongoing activities.

The recommended research agenda would directly address the technology barriers and the regulation and certification barriers. As noted in Table 4.1, although several research projects would address the social and legal issues, the agenda would not address the full range of these issues. In the absence of any other action, resolution of the legal and social barriers will likely take a long time, as court cases are filed to address various issues in various locales on a case-by-case basis, with intermittent legislative action in reaction to highly publicized court cases, accidents, and the like. A more timely and effective approach for resolving the legal and social barriers could begin with discussions involving the Department of Justice, FAA, National Transportation Safety Board, state attorneys general, public interest legal organizations, and aviation community stakeholders. The discussion of some related issues may also be informed by social science research. Given that the FAA is the federal government's lead agency for establishing and implementing aviation regulations, it is in the best position to take the lead in initiating a collaborative and proactive effort to address legal and social barriers.

CONCLUDING REMARKS

Civil aviation in the United States and elsewhere in the world is on the threshold of profound changes in the way it operates because of the rapid evolution of IA systems. Advanced IA systems will, among other things, be able to operate without direct human supervision or control for extended periods of time and over long distances. As happens with any other rapidly evolving technology, early adapters sometimes get caught up in the excitement of the moment, producing a form of intellectual hyperinflation that greatly exaggerates the promise of things to come and greatly underestimates costs in terms of money, time, and—in many cases—unintended consequences or complications. While there is little doubt that over the long run the potential benefits of IA in civil aviation will indeed be great, there should be equally little doubt that getting there, *while maintaining or improving the safety and efficiency of U.S. civil aviation,* will be no easy matter. Furthermore, given that the potential benefits of advanced IA systems—as well as the unintended consequences—will inevitably accrue to some stakeholders much more than others, the enthusiasm of the latter for fielding such systems could be limited. In any case, overcoming the barriers identified in this report by pursuing the research agenda proposed by the committee is a vital next step, although more work beyond the issues identified here will certainly be needed as the nation ventures into this new era of flight.

[2] JPDO, NextGen UAS Research, Development and Demonstration Roadmap, Version 1.0, March 15, 2012, http://www.jpdo.gov/library/20120315_UAS%20RDandD%20Roadmap.pdf.