Enabling Autonomous Flight and Operation in the National Airspace System

Summary of Reduced Crew Operations for Domestic and International Aircraft

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1. Introduction

With an impending pilot shortage, expected growth in aviation, and need for scalability and efficiency to reduce cost, future civil aviation operations are envisioned to take advantage of continuing advances in machine intelligence, data analytics, high-bandwidth and secure data networks, and increasingly capable sensors. Together, these technologies will enable increasingly autonomous systems. Many stakeholders have expressed the value of defining a national strategy to support the introduction of autonomous systems. A strategy that establishes clear goals for enabling operations, characterizes various maturity levels and increasingly autonomous system options, identifies a path towards acceptance, and pulls resources together to conduct tests to assess maturity will have common benefit. Given this interest and deemed usefulness, NASA has been encouraged to take the initiative to facilitate these efforts.

On April 23 and 24, 2019, NASA conducted the first of a series of workshops to bring together stakeholders and define a national strategy to enable increasingly autonomous operations. The workshops focused on identifying needs and use cases for increasingly autonomous civil aviation operations in the National Airspace System (NAS). The first workshop considered two use cases with the potential to be enabled by autonomous systems in the future: reduced crew operations for domestic and international large-transport-category aircraft, and autonomous medium-size cargo/freighter operations. The following is a summary of workshop results for the reduced crew operations use case.

The goals of the workshop were to discuss and identify:

- The minimum viable products to make progress towards increasingly autonomous flight and operations in the NAS
- Where NASA collaboration with industry will be most productive
- Possible collaborative demonstrations
- Steps toward operationalization of increasingly autonomous systems.

To address the workshop objective of developing a national strategy for steps to achieve operational systems, a minimum viable product (MVP) strategy was adopted. An MVP is a product with just enough features to satisfy early customers, and capable of providing feedback for future product development. The MVP strategy directly addresses near-term market needs and business cases, and may be beneficial in addressing long-term multi-phase advancements of complex systems by overcoming unknowns via implementing and operationalizing realizable capabilities as early as possible.

Throughout the workshop, there were several recurring topics that permeated discussions. Safety was a foundational theme, as people explored how to ensure new systems protect people in the air and on the ground. This connected into the need for a new set of policies (including regulations, standards and procedures for certification) to ensure that automation and associated technologies are safe and reliable. So much of this requires understanding the overall architecture and concepts of operation for automated air transportation, which defines what gaps need to be filled and what research is required. The long-term goal of full and complete automation is an ambitious one. Incremental steps towards reaching that goal will be helpful in the short term, but revolutionary advances are also required and that will depend on strategic long-term investments in research and development.

To identify MVPs for aviation automation, participants focused on the near term goal of using automation to support and augment, rather than replace, the human pilot. Automation would be used to provide more robust and resilient systems to fly the aircraft, serving as a digital backup or copilot to the human pilot. This triggered discussion of the different aspects of aircraft piloting, including: functional analysis and decomposition; roles and responsibilities of multiple air crew, the ground, and autopilot; human-machine integration; crew resource management; pilot engagement; and voice and digital communications.

These topics were discussed in two breakout groups. Each breakout group met for three breakout sessions. The notes, discussions, and priorities generated by the breakout group participants are summarized in this report. On the first day, five keynote presentations were made that addressed several topics. Before the first breakout session, an instruction briefing that explained the MVP strategy was presented to participants. The results of all sessions for the two breakout groups were combined and presented to a plenary at the end of the second day. The workshop agenda can be found in Appendix 1: Workshop Agenda.

2. Minimum Viable Products (MVPs)

The first task covered by workshop attendees was to identify needs, MVPs, progression towards their autonomous operations, and needed aircraft, ground, and cloud-based capability levels.

2.1 Identified Needs for RCO (Reduced Crew Operations)

The scope of discussions by the workshop attendees covered all phases of flight with crew in the cockpit. To frame the group conversation, breakout participants expanded the original use case to include additional missions. The missions considered by participants were urban air mobility (UAM), cargo, 14 CFR Part 121 long haul (reduction of off-duty crewmembers), and Part 121 (two crewmembers to one). These are the main missions where there is a potential need for enabling reduced crew operations.

Before defining any minimum viable products, the workshop participants discussed the needs for reduced crew operation, including technology needs, concepts of operation (ConOps) needs, and foundational research needs. This preliminary discussion helped the workshop participants then define their proposed minimum viable products.

There are many things needed to enable reduced crew operations. The following list, developed by participants, sets forth many of those needs:

- Define requirements
- Define roles and responsibilities
    - Redefinition of crew roles and responsibilities with automation support
    - Human-automation teaming research
    - Functional allocation (both dynamic and static)
    - Pilot workload management
- Develop operational standards/concept of operations
- Define automation needs
    - Adaptive
        - Contingency management when pilot is incapacitated
        - Support rule changes by both geographic locality and airspace classes
        - Risk-based decision logic for piloting functions
    - Adaptable (study if and when pilots should have the ability to control the level of automation)
    - Transparent “enough” (allow the pilot to understand why and how things happen if and when appropriate)
    - Trust (both ways)
    - Reliability
    - Simplicity
- Develop method for validating non-deterministic systems
- Develop training of the human operator/pilot to match the level of automation/mode of automation
- Identify and develop requirements for sensor technology and data fusion for:
    - Sense and avoid
    - Decision-making process (e.g., weather threat assessment creating flight path changes)
- Develop techniques or systems to keep single pilot engaged during low activity phases of flight
    - How to quickly re-engage pilot during emergency/anomaly

- Define communication requirements and method between human and machine "pilots"
    - Voice or other?
- Develop communication capability to allow automation of speech
    - DataComm
    - Note: DoD/AFRL automation shows human communication is obsolete; current air traffic requires human interaction
- Identify certification changes/differences
    - Technology and the regulation to support it
    - New ways of meeting intent of rule/regulation could reduce current regulatory barriers
- Identify V&V challenges, NAS integration challenges, etc.
- Develop design guide – "autonomy for dummies"
- Identify and develop required ground infrastructure
- Identify any high workload tasks that can be offloaded or automated to make the tasks simpler, tasks that can be completely replaced, and those tasks that still require human interaction
    - Who decides what needs to be automated? This may be platform and/or mission dependent.
- Define performance-based requirements/expectations for automation–pillars of automation
    - Best practices, architecture, design, failure modes
- Maintain or improve safety
- Encourage data sharing
- Work towards stakeholder acceptance
    - Public acceptance – how to communicate and demonstrate that safety is maintained.

2.2 List of Minimum Viable Products

A minimum viable product can be different things to different people, but essentially it is an incremental product that allows the early testing of a set of features that would be required to be deployed on a fully developed capability. Eric Reis has a widely accepted definition that states, "A minimum viable product is that version of a new product which allows a team to collect the maximum amount of validated learning about customers with the least effort."

Some of the workgroups proposed MVPs that include lower level products that could be combined into a larger market product. Others interpret MVP as a higher-level product that combines these lower level products. Both interpretations are valid, and it is important to note that the included list of MVPs includes both types along with suggested research activities.

1. Develop a capability with automation providing the second seat/virtual co-pilot capabilities.
    - The architecture should be designed to allow for incremental modification to automation by functional allocation (e.g., system health monitoring, automated checklists)
    - The architecture should be designed to automatically pull up procedures for both nominal and off-nominal scenarios to aide pilot
        - i. The system could include checklists
        - ii. The system could provide response guidance to deal with failures

- The architecture should allow for the simulation of reduced crew concepts while allowing researchers to collect system and pilot data (e.g., physiological data, workload)
- The system should also allow for tests of autonomy as a backup (incapacitated pilot, work overload, insufficient engagement)
- The system should allow the user to collect relevant data to inform pilot to co-pilot interaction, co-pilot/monitoring functions, what makes a good co-pilot, DL training database, interaction between pilot and automated system, human contribution to safety, build certification basis
    i. More data sharing (e.g., companies/airline data)
    ii. Self-reporting could help build public acceptance
- The system should allow the user to test best practices for enabling pilot input into automated system; accepting human as a "sensor"
- The system should allow users to test products in a well understood and repeatable manner
- The system should provide users with access to data during off-nominal situations that pilots currently access manually (e.g., safety manual, performance envelopes)
- The system should allow researchers to explore how crew resource management might change with increasing automation*

2. Develop a capability that replaces the co-pilot with an "operator"/co-pilot on the ground (i.e., less rigorous training)*
    - The system should allow users to provide different types of support services (e.g., pilot, dispatch, ATC communications) from the ground
3. Develop a capability that allows for the decrease of long-haul crew members from five to four to three and then to two onboard crew; the capability should allow for the replacement of any lost onboard crew members with "operators" on the ground*
4. Develop a Part 121 capability that allows for zero crew onboard, includes ground monitoring and command center*
    - Include DAA, maneuvers to avoid conflicts, and maneuvers for route optimization
5. Install safety/assurance systems (e.g., Ground Collision Avoidance System (GCAS), Airborne Collision Avoidance System (ACAS)) on general aviation (GA) aircraft to build trust in automation
    - More aircraft with TCAS
    - Link systems such as DAA to autopilot, test aircraft to aircraft
    - Provide for the digital communication of information between ATC and the aircraft/automation to support the future ATMx (air traffic management exploration).
6. Develop a capability that allows for the test of individual components of reduced crew operations such as auto-taxi, auto-land.

* Note that all sub-bullets in MVP item #1 also apply to items 2, 3, and 4.

2.3 Progression to Move Towards Autonomous Operations

Workshop participants agreed that there are a number of steps to move toward autonomous operations. The first step would be to reduce the crew requirements on long haul flights and then incrementally work towards flights with a single pilot and then, potentially, fully autonomous operations without a pilot on board. The recommended transitions would be:

- From five-, four-, three-member crews to two crew members
- From two- to one-crew member
- From two to operator
- From one to operator
- From one to no crew

Taking a crawl-walk-run approach will allow time to grow acceptance of a fully autonomous vision, build a proven safety case, and help the pilot be better at their job. This also means starting on a small scale with low risk and gradually scale up to more complexity. For instance, one proposal was to start with long haul cargo flights in remote areas as a way to experiment and test new missions in a lower risk context. This will also allow researchers to initially use automation as a back up to a second pilot, collect necessary performance data, while slowly increasing the capability of the automation until such time when the second pilot can be safely removed. It would also allow researchers to explore important issues related to the design of future human machine interfaces, potential changes to crew resource management, pilot engagement as pilot roles and responsibilities change, and any functional allocation changes required as we move towards more autonomous operations.

3. Research Gaps, Needs, and Implementation Strategy for Increasingly Autonomous Operations

Research needs and gaps are heavily dependent on the vehicle and airspace architecture, as well as the diverse concepts of operation. Several key issues were identified in the context of reduced crew operations, as follows:

1. Identify and describe crew resource management characteristics, specifically in the context of a copilot.
    - For cases where the reduced crew being considered involves moving from a pilot/co-pilot paradigm to a single pilot operation augmented by automation, the notion of task and role reallocation may require the development of novel crew resource management paradigms, specifically when the other crewmember is an automated agent.
    - For cases when the reduced crew being considered involved a reduction in crew from many to two or more (e.g., relief crew on long haul flights), models for crew intervention in contingency scenarios may need to be revisited.
    - The reduction from two (or more) to no crew was not considered for this topic.
2. Identify potential tasks that are candidates to be re-allocated to automation.
    - Identify tasks which may no longer be able to be performed by the remaining crewmember(s), given their limited resources, will depend on the ConOps.
    - Identify tasks that may be performed by the automation will depend on the vehicle architecture and constraints.
    - Develop a strategy of how this reallocation may take place will be a significant effort.
3. Determine requirements for interoperability of reduced crew operations with current airspace procedures and practices.
    - Focus on interoperability of autonomous vehicles with dispatch, and (remote) pilots.
    - Consider how autonomous systems integrate with ATC/ATM automation (e.g., ERAM) is of particular interest.
4. Identify onboard sensing and perception capabilities and vehicle requirements for reduced crew/autonomous operation.
5. Identify information and communication requirements between agents (e.g., vehicle, operator, ATC etc.).
    - What functions will require voice communications vs data communications.
    - How will communication be handled in autonomous/remote operations (e.g., ATC communications, sector handoffs, etc.).
    - How will vehicle health data be communicated, and to whom.
6. Identify contingency procedures, specifically for loss of communications (e.g., contingencies) in the context of autonomous/remotely piloted vehicles.
7. Develop an ecosystem-wide platform to test products in a well-understood and repeatable manner to make advances in system development.

A primary implementation strategy proposed to enable the operation of increasingly autonomous systems in a complex airspace involves defining the architecture (both vehicle and airspace) and building a test platform that has the automation fully integrated. Automation functional allocation could then be incrementally increased and tested to prototype new operations and technologies.

There was, however, some concern that if research planning is too tactical, that larger-scope advances wouldn’t be addressed. There needs to be a balance between the near term transition of automation and a larger scope acceptance of a fully autonomous vision, as well as an investment in longer term, strategic research.

4. Action Plan for Collective Demonstrations

As we move towards reduced crew operations with the ultimate goal of enabling unmanned operations, we need a cohesive plan for research and demonstrations that will lead us towards that goal. There is not simply one demonstration that will be dispositive in providing the required evidence–based support for reduced crew operations, and so the group endeavored to propose a series of activities that will help move us towards this goal. Most attendees agreed that any collective demonstrations should be developed with the goal of first moving from two pilots to a single pilot. Support for that reduction could come from either an increase in onboard automation or an increase in support from the ground either in the form of a ground pilot or ground-based automation, or both. These collective demonstrations and any required laboratory infrastructure should be built to allow researchers to test reduced operations with all of these possible configurations of co-pilot and automation support, along with the integration of any minimum viable products as enumerated in Section 2.

The group proposed moving forward with a demonstration where the co-pilot is moved from the cockpit to the ground. The group also believed that it would be beneficial to develop a testbed simulation capability for piloting the reduced-crew operations concept before testing it in a live flight demonstration. We expect that any initial live flight test of reduced crew operations would employ the nominal case as to make a minimal impact on safety. Given safety risk management concerns, some suggested having initial flight tests of the co-pilot-on-the-ground concept in a general aviation(GA) vehicle. Providing a co-pilot on the ground for a GA pilot might be viewed as an addition to safety, whereas removing a pilot from a larger aircraft might be viewed as a reduction in safety and might impact or delay the required approvals from the FAA.

Given how safety considerations are critical, the group also proposed including the FAA in these demonstrations, while jointly working towards defining the regulations necessary to test and ultimately enable reduced crew operations. The proposed demonstrations and testbed would also allow different companies to test their equipment in an unbiased environment. Researchers could also use the testbed to test stress cases using human-in-the loop simulations and without affecting the safety of the national airspace system. This would also allow researchers to begin to identify the impact of reduced crew operations on crew resource management, crew workload, and task allocation between the pilot on board, the pilot on the ground, and the automation. It is important to note that one of the primary aims of these proposed demonstrations would be to produce data that will be necessary to support the safety case for reduced crew operations.

5. Collaboration Topics Where NASA Research Could Help

Participants identified several NASA research topic areas that would facilitate advancement toward approved operations with reduced crew. Identified topics are:

- Function reallocation: define and validate the allocation of functions between remaining crew and new airborne automation.
    - Identify candidate functions for airborne automation, airborne humans, and ground-based humans and automation.
        - Monitoring is not a task best-suited for human operators,
        - Is it better and/or more efficient to have localized automation versus ground-based support providing automation and data to the aircraft?
    - Determine whether the new human/automation team introduces requirements for new functions.
    - Establish crew interface requirements, including the design of displays.
    - Determine data visualization and data fusion requirements.
- Human-machine interaction: Integrate remaining human crew and automation into a fully-functioning team.
    - Define and establish requirements for crew resource management (CRM) for the new paradigm of a mixed human/machine crew.
    - Consider formerly capturing current crewmember interactions as a step toward replacing crewmembers with automation.
    - Conduct experiments replacing human crew members with automation.
- Training: Define training requirements and establish new approaches for ensuring proficiency for the remaining flight crew.
    - Determine how to replace current approaches to on-the-job training that rely on the current-day crew size.
- Investigate the need for standardization and commonality across aircraft types to facilitate reduced crew operations.
    - Handling/flying qualities.
    - Common autonomy interface.
- Determine whether airframe-specific limitations or differences may impact automation or functions required for reduced-crew operations.
- Identify the social impacts, costs, and benefits of a pilot operating an aircraft without on-board human interaction.
    - Is safety impacted by the loss of human/social interaction?
    - If needed, how can automation introduce human-like engagement?
    - Determine who to address the topic of public perception.
- Identify impacts to cybersecurity and the need for special cybersecurity requirements to support reduced crew operations.

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Appendix 1: Workshop Agenda

ENABLING AUTONOMOUS FLIGHT AND OPERATIONS IN THE NATIONAL AIRSPACE SYSTEM WORKSHOP 1 TUESDAY, APRIL 23, 2019 (DAY 1)		
TIME	**ITEM**	**PRESENTER**
7:30am – 8:30am	Registration	
8:30am – 8:45am	Welcome, Logistics, and Workshop Goals	Dr. Parimal Kopardekar Acting Director, NARI, NASA
8:45am – 9:00am	**OVERVIEW:** NASA Aeronautics' Vision	Dr. Jaiwon Shin Associate Administrator, ARMD, NASA
9:00am – 9:30am	**KEYNOTE:** Lessons Learned from Autonomous Cars	Dr. Sebastian Thrun CEO, Kitty Hawk Corporation
9:30am – 10:00am	**KEYNOTE:** Lessons Learned from Autonomous Small UAS	Dr. Sanjiv Singh CEO, Near Earth Autonomy
10:00am – 10:30am	*Break*	*All*
10:30am – 10:45am	**KEYNOTE:** Reduced Crew Operations	Raj Singh Managing Director, JetBlue Technology Ventures
10:45am – 11:15am	**KEYNOTE:** Certification Considerations for Autonomous Flight & Ops	Dr. Michael Romanowski Director, Policy & Innovation, Aircraft Certification Service, FAA
11:15am – 12:15pm	**KEYNOTE:** Perspective on Autonomous Mid-size Cargo /Freighters & Reduced Crew Transport-Category Aircraft	Joseph Keegan Director, Autonomous Systems and Disruptive Mobility, The Boeing Company
12:15pm –12:30pm	Breakout session instructions	Dr. Parimal Kopardekar
12:30am – 1:30pm	*Lunch*	*All*
1:30pm – 4:30pm	**BREAKOUT SESSION 1:** Identify needs, MVPs, & progression towards autonomous operation, including ground systems & cloud-based capability levels.	Vanessa Aubuchon, NASA Ferne Friedman-Berg, FAA Sandy Lozito, NASA Jill Marlowe, NASA
4:30pm – 5:00pm	Wrap-up	Dr. Parimal Kopardekar

ENABLING AUTONOMOUS FLIGHT AND OPERATIONS IN THE NATIONAL AIRSPACE SYSTEM WORKSHOP 1 WEDNESDAY, APRIL 24, 2019 (DAY 2)		
TIME	**ITEM**	**PRESENTER**
8:00am – 8:30am	**KEYNOTE:** FAA & Innovation	Carl Burleson Acting Deputy Administrator, FAA
8:30am – 9:45am	**PANEL:** Autonomy Considerations, Operational Needs, and Research Gaps Moderator: Dr. John Cavolowsky, Director, Transformative Aeronautics Concepts Program, NASA	Prof. Ella Atkins, University of Michigan Andy Lacher, MITRE – ASTM Prof. Amy Pritchett, Penn State University Wes Ryan, FAA Capt. Bill Secord, FedEx – Air Line Pilots Assoc.
9:45am – 10:00am	*Break*	*All*
10:00am –11:30am	**BREAKOUT SESSION 2:** Identify research gaps, needs, & strategy to implement increasingly autonomous ops in complex airspace and areas.	Irene Gregory, NASA Husni Idris, NASA Wes Ryan, FAA Confesor Santiago, NASA
11:30am – 12:30pm	*Lunch*	*All*
12:30pm – 2:00pm	**BREAKOUT SESSION 3:** Identify action plan for collective demonstrations & operational implementation of increasingly autonomous systems in the NAS	Karen Tung Cate, NASA Natasha Neogi, NASA Mark Skoog, NASA Chris Teubert, NASA
2:00pm – 2:15pm	*Break*	*All*
2:15pm – 3:30pm	**BREAKOUT SESSIONS 1-3 REPORT:** Autonomous Medium-size Cargo/Freighters	Chris Teubert, NASA
3:30pm – 4:45pm	**BREAKOUT SESSIONS 1-3 REPORT:** RCO for Domestic & International Aircraft	Vanessa Aubuchon, NASA
4:45pm – 5:00pm	Wrap-up and Next Steps	Dr. Parimal Kopardekar