Who's got the bridge? –
Towards Safe, Robust Autonomous Operations at NASA Langley's Autonomy Incubator

"Data, you've got the bridge." – First Officer Thomas "Will" Riker
Star Trek: The Next Generation:: Coming of Age (1988)

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NASA aeronautics research has made decades of contributions to aviation. Both aircraft and air traffic management (ATM) systems in use today contain NASA-developed and NASA-sponsored technologies that improve safety and efficiency. Recent innovations in robotics and autonomy for automobiles and unmanned systems point to a future with increased personal mobility and access to transportation, including aviation. Automation and autonomous operations will transform the way we move people and goods. Achieving this mobility will require safe, robust, reliable operations for both the vehicle and the airspace and challenges to this inevitable future are being addressed now in government labs, universities, and industry. These challenges are the focus of NASA Langley Research Center's Autonomy Incubator whose R&D portfolio includes mission planning, trajectory and path planning, object detection and avoidance, object classification, sensor fusion, controls, machine learning, computer vision, human-machine teaming, geo-containment, open architecture design and development, as well as the test and evaluation environment that will be critical to prove system reliability and support certification. Safe autonomous operations will be enabled via onboard sensing and perception systems in both data-rich and data-deprived environments. Applied autonomy will enable safety, efficiency and unprecedented mobility as people and goods take to the skies tomorrow just as we do on the road today.

Nomenclature and Acronyms

AACUS	Autonomous Aerial Cargo Utility System
AEON	Autonomous Entity Operations Network
AI	Autonomy Incubator
ALIAS	Aircrew Labor In-Cockpit Automation System
ALHAT	Autonomous Landing and Hazard Avoidance Technology
ARES	Aerial Reconfigurable Embedded System
ATM	Air Traffic Management
BLOS	Beyond Line Of Sight

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CERTAIN	City Environment for Range Testing of Autonomous Integrated Navigation
CODE	Cooperative Operations in Denied Environments
DARPA	Defense Advanced Research Projects Agency
DDS	Data Distribution Service
DSB	Defense Science Board
FPV	First Person View
HITL	Hardware-In-The-Loop
HSI	Human System Interaction
ISS	International Space Station
LaRC	*L*angley Research Center
MAAP	Mid-Atlantic Aviation Partnership
ONR	Office of Naval Research
OODA	Observe Orient Decide Act
PI	Principle Investigator
R&D	Research & Development
ROS	Robot Operating System
SA	Situation Awareness
UAS	Unmanned Aerial System
VTOL	Vertical Take Off and Landing

I.   Introduction

THE Autonomy Incubator (AI) at NASA Langley Research Center (LaRC) was established in the spring of 2014 to prepare the center workforce to meet the autonomy challenges that are anticipated in science, space exploration, and aeronautics as the NASA mission directorates look to enable new missions such as asteroid retrieval, planetary exploration, atmospheric sensing in historically inaccessible areas, and the integration of Unmanned Aerial Systems (UAS) into our everyday lives – all missions of increasing complexity, distance, proximity, pace, and/or accessibility. Building on decades of experience and success in the design, fabrication, and integration of safe and reliable automated systems for space and aeronautics, the LaRC Autonomy Incubator seeks to bridge the chasm between automation and autonomy and build systems that are capable of

1. sensing and perceiving their environments
2. assessing their state
3. making decisions in the face of uncertainty and with incomplete information
4. acting on those decisions and
5. learning from that experience.

These autonomous systems will be non-deterministic and adaptive in much the same way that humans are. These systems (and/or the agents that comprise them) will earn trust (or lose it) much like humans. If successful, these intelligent agents will be able to transfer knowledge learned in one context to another (e.g., like a pilot transfer knowledge from one aircraft to another or a driver from one automobile to another) and acquire knowledge from other agents in the system.

The Autonomy Incubator is a co-located team composed of researchers from multiple areas of expertise including but not limited to computer science, robotics, electrical engineering, mechanical engineering, aerospace engineering, psychology, machine vision, and machine learning. These Principle Investigators (PIs) are supported by qualified UAS pilots, flight safety personnel, range safety officers, and technicians. The team works together in an Agile work environment towards a common technical challenge around autonomous operations across NASA mission domains.

II.   Automation vs. Autonomy

The distinction between automation and autonomy is not universally agreed upon. There are many models available for consideration, each with its own valid perspective and emphasis. Some assert that there is a continuum between human control with no assistance from the computer (human does it all) and computer decides everything (ignoring the human)[1]. This idea of "ignoring the human" implies that there is a human in the loop who might be observing but has no ability to intervene in the mission. Even though the definitions were created decades apart, this is consistent with the ICAO definition that an autonomous aircraft is "an unmanned aircraft that does not allow pilot intervention in the management of the flight"[2]. Other models base the distinction between automation and autonomy on complexity, again with a continuum between automation and autonomy, but based on whether the computer is acting as an expert (behaving expertly in a limited area of performance) vs. a decision support tool (helping the human

perform better perform his/her responsibilities). NASA's Spacecraft Mission and Assessment and Replanning Tool (SMART)[3] is based on the OODA loop and divides each category (Observe, Orient, Decide, Act) into eight levels based on (as with [1]) function allocation between the human and the computer. The Department of Defense (DoD) Defense Science Board (DSB) asserts that the DoD should abandon the use of autonomy scales altogether and embrace a three-facet autonomous systems framework composed of cognitive echelon, mission timelines, and human-machine system trade spaces[4]. In this assertion, the DSB eliminates the point of confusion about automation and autonomy. Any scale that presents a continuum implies, whether intended or not, that the end state of "autonomy" can be achieved by increasing "automation" until some tipping point is reached, whether that continuum is based on human involvement or machine complexity or the approach to decision-making.

While there may be some truth to the idea that sufficiently advanced automation is indistinguishable from autonomy (appropriated from Arthur C. Clarke's Three Laws[5]) especially when viewed from "the outside" or from the perspective of human-system interaction (HSI), it is what's happening "under the hood" and, consequently, how these systems respond to new situations that distinguishes automation from autonomy. From the perspective of machine capabilities, the transition from automation to autonomy is a discrete step – a chasm[6]. In the transition from automation to autonomy, we move from systems that take predetermined action in (typically) structured and static environments to systems in dynamic and unstructured environments that sense and reason about their perceived state, assess that state for situation awareness (SA), and take action based on that SA. An autonomous system (or agent in that system) should be able to make decisions with incomplete or uncertain information or in the face of a new situation. This means that an intelligent agent in an autonomous system must be able to transfer knowledge from one situation to another and/or seek "advice" from other agents in the system and that truly autonomous systems will *learn* – from their own experiences and from each other. They will be non-deterministic and behaviors will emerge as the subsystem evolves over time. More simply stated[7]:

> The distinction between automation and autonomy is essentially the difference between relegation—assigning discrete, easily performed tasks—and delegation—assigning a given set of mission parameters…it's the difference between machine-based execution and machine-based decision-making.

In short, an autonomous system "has the bridge" or "the conn" when the commander or supervisor is not in or on the loop. Therefore, while the "Captain", who is responsible for defining the mission, may have stepped away (or is so remote that s/he cannot tactically command), an autonomous system must have the authority and ability to redirect itself within some set of overarching mission goals based on its perceptions and processing without needing the explicit consent or direction of a human operator or user[8].

III. We Are Not Alone

The Autonomy Incubator is one of many organizations researching and developing technologies and capabilities while working towards autonomous operations and including every effort at every university, company, and government agency that is rising to the autonomy challenge would be impossible. The following are a handful of research efforts that NASA is either leading or has direct involvement with either through cooperative research or via subject matter expertise. NASA's Robonaut[9] is currently onboard the International Space Station (ISS) working alongside human crewmembers (Figure 1). The Defense Advanced Research Projects Agency (DARPA) Transformer TX program[10] initially aimed to build a "ground vehicle that is capable of configuring into a VTOL air vehicle with a maximum payload capability of approximately 1,000 lbs." and has transitioned to Aerial Reconfigurable Embedded System (ARES) in Phase II, a VTOL flight module capable of carrying interchangeable mission-specific modules ranging from cargo to CASEVAC. The DARPA Aircrew Labor In-Cockpit Automation System (ALIAS) program envisions a "tailorable, drop-in, removable [robotic] kit that would enable high levels of automation in existing aircraft and facilitate reduced need for onboard crew"[11]. The ALIAS program also contains a Knowledge Acquisition component that speaks to machines learning to pilot an aircraft in a way similar to human learning. The DARPA Collaborative Operations in Denied Environment (CODE) program is focused on collaborative autonomy in denied or contested airspace and aims to create a capability such that "unmanned vehicles would continuously evaluate themselves and their environment and present recommendations for UAV team actions" to a single human mission supervisor"[12] for review and consent. ONR's Autonomous Aerial Cargo Utility System (AACUS)[13] is an Innovative Naval Prototype (INP) that has demonstrated the feasibility of fully autonomous cargo delivery by an unmanned rotary wing vehicle capable of sensing and selecting a safe landing site in an area specified by a soldier in the field using a handheld tablet. In an effort similar to AACUS but focused on lunar landing, NASA's Autonomous Landing and Hazard Avoidance Technology (ALHAT)[14] has demonstrated the ability to navigate and determine safe landing sites

on planetary surfaces (Figure 1). A suite of sensors and associated algorithms create an elevation map of the landing site to identify the location of hazards such as rock piles and craters and provide range and velocity data along with altitude measurements to help the vehicle locate the surface and land safely.

Figure 1: Robonaut 2 and ALHAT (image credit NASA)

IV. Our Mission

In addition to recommending the abandonment of autonomy levels, the DSB[4] identified autonomy "gaps" and many of the AI's ongoing R&D efforts are focused on these gap areas.

- Most use of *learning for autonomous navigation* has been applied to ground vehicles and robots. One important area for future development in adaptive navigation is to refine the existing learning methods for effective use *in alternative domains such as air* and marine vehicles.
- Most UxVs are required to operate in *environments that are both unstructured and dynamic*, where existing maps provide little guidance. Developing *learning methods* that can cope with such *complex environments* is an important challenge.

The AI is exploring both traditional solutions as well as machine-learning based-approaches in these gap areas.

The mission of NASA LaRC's Autonomy Incubator is to rise to the challenge of data-degraded/deprived navigation in dynamic and unstructured environments. This is a an R&D challenge that must be met for NASA to retrieve an asteroid, explore planetary surfaces, measure pollution in historically inaccessible areas, and enable the integration of UAS into our National Airspace System (NAS) as well as our everyday lives. The AI has been focused on aerial navigation but these future NASA mission will require robotic solutions across space, air, sea, and land and we have begun broadening our portfolio to include multimodal navigation and payload delivery solutions. Further, we are exploring the efficacy of machine learning solutions in some aspects of this autonomous navigation problem space.

A. Open Architecture

A critical characteristic of our incubator effort is the ability to explore alternate methods and quickly integrate external solutions, and so we need a software architecture and framework that supports collaboration, interoperability, and scalability. We have designed and implemented an open architecture that employs Data Distribution Service (DDS) for Real-Time Systems for messaging middleware. DDS[15] is a publish-subscribe model (not unlike ROS, Robot Operating System[16]) to take advantage of "plug-n-play" network topologies, portability between systems, Quality of Service (QoS) guarantees between software entities, and a abstracted interface that external entities can meet without becoming experts in DDS. Further, DDS moves away from the idea of a "core" process and the associated risk of a single point of failure to a distributed entity-to-entity middleware approach.

The Autonomous Entity Operations Network (AEON)[17] is an open distributed software architecture and a highly configurable data fusion framework that provides plug-and-play compatibility with a wide array of computer systems, sensors, software, and controls hardware. It also supports a ground control system(s) that acts as a test-bed for integration of multi-modal robotic vehicles.

B. Intelligent Flight Systems

The Autonomy Incubator falls under a broad area of innovation at NASA LaRC called Intelligent Flight Systems (IFS). IFS includes innovative vehicle design[18], state-of-the-art wind tunnels[19], cutting-edge sensors[20], and advanced algorithms[21]. The AI focus is on algorithm development along with system design, integration, and test and utilizes procured vehicles and sensors from industry, academia, and other government organizations inside and outside of NASA.

Autonomous mobility can be decomposed into a number of fundamental tasks. Assuming that a mission plan is available, an intelligent agent in the system must be able to:

- Estimate its (ownship) state
- Sense and perceive its world
- Maintain and update its "map" of the world
- Fuse information from multiple sensor sources
- Detect and avoid objects/hazards
- Classify objects as benign or hazardous
- (Re)Plan its trajectory and path
- Execute inner loop control for agile flight

These tasks can and have been accomplished using traditional approaches – approaches applied successfully in ground robotics, adaptive control, etc. Within the AI, we are pursuing the advancement and integration of these more traditional (yet still groundbreaking) solutions as well as approaches that incorporate unsupervised, supervised, and reinforcement learning techniques.

In the area of decision-making in critical phases of flight, we are currently applying supervised machine learning techniques to determining whether to "go around" during the automated landing approach of an unmanned fixed wing experimental testbed aircraft[22]. Initial tests of the go around decision capability focused on the transition from hardware-in-the-loop (HITL) simulation to actual flight tests (Figure 2) using a simple altitude threshold for the go around criteria. Additional relevant criteria such as centerline offset, glideslope error, estimated fuel remaining, as well as gust-induced transients are being incorporated into the learning model. The overall go around decision has been decomposed into lower level components to investigate the applicability of both supervised and unsupervised machine learning techniques.

Figure 2: Automatic Go-Around Initiated at 200' AGL Due to Glide Slope Error

A mission of particular interest to NASA is data collection in remote, cluttered environments such as under the tree canopy (e.g., rain forest) for Earth science. By applying reinforcement learning techniques to input from human operators, not unlike first person view (FPV) drone racing, the efficacy of a data set aggregation for this mission is being assessed[23]. Using video from a single forward-facing camera, computer vision based features relating to edge and gradient information are extracted and correlated with commands from a human operator to teach the autonomous system how to navigate around trees and other natural objects in an unmapped and cluttered forest environment. The software-in-the-loop simulation (SILSIM) and indoor flight test setup are shown in Figure 3.

Figure 3: Software-in-the-Loop Simulation and Indoor flight test of an "Under the Tree Canopy" Mission

An effective flight through a forest or in a disaster area requires a compelling pace of operations in terms of speed and agility. In support of these demanding missions, the AEON Flight Control System (AEON-FCS) is being developed. The AEON-FCS[24] is capable of implementing both classic guidance, navigation, and control (GNC) law algorithms in a centralized system architecture as well as a fully distributed control system, like AEON. This will allow a system design to break away from a centralized approach and place an AEON processor and inertial sensor set located close to the control effector(s), extending the distributed programming paradigm deep into the inner-loop. This distributed programming paradigm may also enable a data-centric approach to control laws such that a controller may be capable of being event driven rather than time synchronized enabling the performance gains required to realize challenging agile missions like under the canopy and surveillance and/or package delivery under the tree canopy or in dynamic unstructured environments such as disaster areas.

There exists a large body of work in the area of object detection (and avoidance) utilizing any number of sensor modalities and algorithmic approaches. The Autonomy Incubator is pursuing ensemble learning and recognition system solutions for classifying an object once it has been detected. Target identification/classification, for at least the distinction between benign and hazardous objects or landing zones, is a critical functionality in autonomous navigation. A Bayesian inference approach[25] can be used to construct an initial set of known objects (training), distinguish between similar yet different objects in real-time, and update the systems belief space with respect to the world map. This classification is possible even in the presence of conflicting information from independent methods or algorithms contributing to the system-wide sensing and perception capability.

Safe, reliable autonomous operations liberate the human operator from the duties of manual flight control or even the required knowledge of a pilot Instead, the human operator will likely be a scientist or a member of the general public who will set high-level supervisory goals and expect the system to execute the prescribed mission. In support of mission planning, the AI is exploring human-machine teaming approaches that employ natural language and gesture recognition[26] rather than a mouse and keyboard. With this ability of the system to understand both speech and gestures, operators unfamiliar with vehicle dynamics will be able to easily plan, initiate, and modify missions using interaction techniques that are familiar to them. This will foster better teaming between the operator and the autonomous agent which will help lower workload, increase situation awareness, and improve performance of the system as a whole.

C. Test & Evaluation

Access to relevant test environments is a challenge for aerial autonomous systems, whether airborne or spaceborne. Restrictions on autonomous and Beyond Line of Sight (BLOS) flight limit UAV access to airspace. Efforts such as the Mid-Atlantic Aviation Partnership (MAAP)[27] and the recent uptick in FAA 333 Exemptions are a step in the right direction but do not yet provide the instantaneous access to flight operational areas that are needed in the AI's Agile approach to R&D. To that end, LaRC has initiated City Environment for Range Testing of Autonomous Integrated Navigation (CERTAIN). CERTAIN is a portfolio of complex environments (Figure 4) within which the challenges of UAS can be mastered. Customers can move from an indoor flight area of over 70,000 cubic feet in the Langley Autonomy and Robotics Center (home of the AI) to two types of contained outdoor flight (tethered and caged) and finally to outdoor flight in NASA LaRC's onsite Phase I COA area. The NASA LaRC campus allows for overflight of urban landmarks, suburban buildings, and forested areas. The AI recently demonstrated an indoor GPS emulation[28] capability that enables vehicles to fly seamlessly between indoor and outdoor environments without loss of signal.
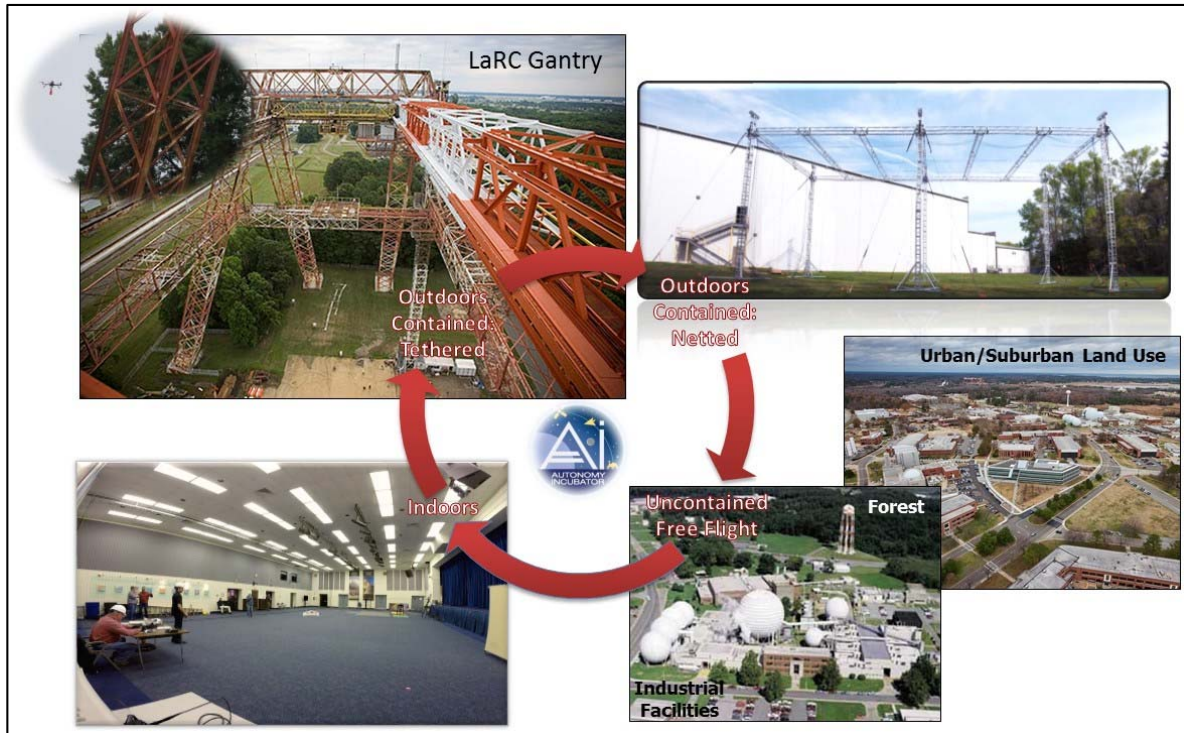
Figure 4: NASA LaRC's Operational Flight Areas

V. Conclusions

NASA LaRC's Autonomy Incubator is focused on the technologies and capabilities that will be required to achieve autonomous missions in the domains of space exploration, aeronautics, and science. Building on decades of experience and success in the design, fabrication, and integration of safe and reliable automated systems for space and aeronautics, we are working towards a verifiable safe software architecture that supports rapid integration of software and hardware by leveraging community standards such as DDS and abstracting hardware-specific interfaces away from software system interfaces. Specific technologies and capabilities included in the AI R&D portfolio are object classification, agile control, human-machine teaming, machine learning, and decision-making in critical phases of flight. Additionally, the AI is guiding the first generation of an on-site T&E environment for performance assessment of autonomous aerial systems from both inside and outside of NASA.

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