BEYOND PIXIE DUST

A Framework for Understanding and Developing Autonomy in Unmanned Aircraft

MITCHELL INSTITUTE for Aerospace Studies

Heather R. Penney
Maj Christopher Olsen, USAF
with Lt Gen David A. Deptula, USAF (Ret.)

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About the Authors

Heather R. Penney is a senior resident fellow at the Mitchell Institute, where she conducts research and analysis on defense policy, focusing on the critical advantage of aerospace power. Prior to joining Mitchell Institute, Penney worked in the aerospace and defense industry, leading budget analysis activities, program execution, and campaign management. An Air Force veteran and pilot, Penney served in the Washington, DC Air National Guard flying F-16s and G-100s and has also served in the Air Force Reserve in the National Military Command Center.

Maj Christopher Olsen is an active duty Air Force officer currently serving as the Military Deputy to the Department of the Air Force Chief Software Officer. Before his current assignment, Maj Olsen was as an Air Force Fellow at the Mitchell Institute for Aerospace Studies. Other notable assignments include Flight Commander, 34th Intelligence Squadron; RC-SW Detachment OIC (deployed), 777th Expeditionary Prime BEEF Squadron; Director of Operations for Autonomy, Power and Control Division, Air Force Research Laboratory; and Executive Officer to the Commander, Air Force Research Laboratory. Major Olsen received an ROTC commission from Texas A&M University in 2008 with a Bachelor of Science in Mechanical Engineering. He also holds a Master of Science in Systems Engineering and a Doctor of Philosophy in Aeronautical Engineering from the Air Force Institute of Technology.

Lt Gen David A. Deptula, USAF (Ret.) is the dean of the Mitchell Institute for Aerospace Studies. A decorated military leader, Deptula has significant experience in combat and has held leadership roles in several major joint contingency operations, where he planned, flew, and commanded aerospace operations. These ranged from humanitarian relief efforts to major theater war. Deptula served as the principal attack planner for the Operation Desert Storm air campaign, was commander of the Combined Task Force for Operation Northern Watch, directed the air campaign over Afghanistan as part of the initial combat operations in Operation Enduring Freedom, and twice served as a joint task force commander. In 2005, he served as the air commander for Operation Unified Assistance, the South Asia tsunami relief effort. Deptula has more than 3,000 flying hours over the course of his military service (400 of which were in combat), to include multiple command assignments in the F-15. In his last assignment, as the Air Force's first deputy chief of staff for intelligence, surveillance, and reconnaissance (ISR), he transformed the U.S. military's ISR and remotely piloted aircraft (RPA) enterprises. From the University of Virginia, Deptula holds a B.A. in astronomy and an M.S. in systems engineering. He also holds an M.S. in national security strategy from the National War College at Fort McNair, Washington, DC. Deptula is a prolific author on aerospace power, and a thought leader on national defense, strategy, and ISR.

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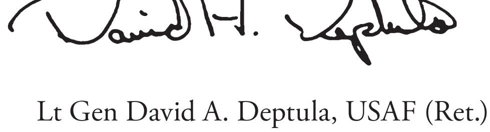
Foreword

The Air Force is now rapidly evolving new concepts for teaming manned fighters and bombers with autonomous UAVs—called manned-unmanned teaming (MUM-T)—to perform strikes, counterair, electronic warfare, and other missions. The goal is to deliver a set of options that significantly increases operational capabilities and capacity beyond what is available today. An added incentive to actualize these capabilities in the near term is the anticipated cost advantages relative to inhabited aircraft mission applications.

The attention given to artificial intelligence (AI), autonomy, and machine-to-machine learning in recent years has resulted in an explosion of ideas regarding how to best incorporate these functions into a variety of military applications. Key among these is how they can be used to enhance capabilities and desired effects when applied to unmanned aerial vehicles (UAVs). While there are plenty of great ideas involving the application of these elements, the challenge is getting the technology readiness levels for those ideas from low to high, and then across the "valley of death" from the research and development realm into the operational force as rapidly as possible.

Differing institutional perspectives long existent between warfighters and engineers have created challenges between aircraft operational expectations and actual aircraft designs that have plagued both since airplanes were first built. This has yielded a disjointed military aviation enterprise where effectiveness and efficiency are not what they could have been or can be. In this report, Heather Penney and Chris Olsen provide a valuable contribution to solving this challenge as it applies to autonomy in conjunction with efforts to achieve effective MUM-T capabilities. They propose a two-part framework consisting of the "Warfighter View" and an "Engineer View" of autonomy. The Warfighter View defines different levels of autonomy needed for UAVs to perform core aircraft control, mission, and teaming functions. The "Engineer View" can then use the warfighter perspective to define and develop specific technologies and systems to meet operational needs.

The significance of this framework is that it stands to provide the Air Force and the other services the means to right-size and accelerate the development and fielding of autonomous UAV teammates that will maintain a technological edge over America's strategic competitors. Their work stands to make a real contribution for defense strategists, policymakers, the aircraft manufacturing industry, and warfighters by offering a means to achieve a pragmatic understanding of autonomy, artificial intelligence, and their application with UAVs to enable new operational capabilities at reduced cost, and in shorter timeframes than traditional aircraft development.



Lt Gen David A. Deptula, USAF (Ret.)
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Key Points

- Teaming increasingly autonomous UAVs with manned aircraft will be critical to developing future air forces that have the resilience, capacity, and lethality needed to compete and win in a peer conflict.
- Defense strategists, policymakers, and warfighters lack an in-depth understanding of autonomy, artificial intelligence, and their current technology readiness levels. This can breed mistrust and resistance to adopting these crucial technologies.
- A framework is required to help the U.S. defense community better understand different autonomous functions and then define and develop systems with the appropriate levels of autonomy needed for MUM-T operations.
- A two-part framework consisting of the "Warfighter View" and "Engineer View" of autonomy is needed to guide the enterprise. The Warfighter View defines different levels of autonomy needed for UAVs to perform functions that the aerospace engineering community—the Engineer View—can then use to define and develop the necessary technologies and systems.
- This framework will help the Air Force and DOD to right-size and accelerate the development and fielding of next-generation autonomous UAV teammates that will maintain a technological edge over America's strategic competitors.

Abstract

Nearly every vision, strategy, and flight plan the U.S. Air Force has released over the past decade identified next-generation unmanned aircraft, autonomy, and artificial intelligence as technologies that are critical to securing a decisive combat advantage in future battlespaces. The Air Force is now developing new operational concepts for teaming manned fighters and bombers with autonomous unmanned aerial vehicles (UAV)—called manned-unmanned teaming (MUM-T)—to perform strikes, counterair, electronic warfare, and other missions. Developing this capability is challenging given the disconnect that often exists between warfighters and engineers.

Warfighters presently do not have a sufficient comprehension of what kind of and how much autonomy is needed for UAVs to achieve desired behaviors. Engineers, on the other hand, often do not fully understand how to decompose warfighter operational performance requirements in ways that enable them to rapidly field effective systems. Crucially, the connections between desired warfighter effects and the technological pathways to implement them are ill-defined. Consequently, the associated visions, strategies, flight plans, operational concepts, programs, and myriad research and development efforts for autonomous teaming aircraft (ATA) have not come together in a clear and coherent way.

A framework that represents both the warfighter and the engineer perspectives would provide a structure and common understanding for these two communities in creating autonomous systems. The "Warfighter View" represents how warfighters organize mental tasks in the battlespace that could integrate different levels of autonomy. The "Engineer View" can then use these tasks to develop the specific algorithms, technologies, and systems necessary to deliver autonomous teaming aircraft that meet the needs and expectations of warfighters. This paper proposes a framework to help Air Force warfighters, strategists, and policymakers better understand autonomous technologies and help guide the enterprise toward future AI-empowered U.S. operations.

Introduction

Nearly every vision, strategy, and flight plan the U.S. Air Force has released over the past decade identified next-generation unmanned aircraft, autonomy, and artificial intelligence as technologies that are critical to securing a decisive combat advantage in future battlespaces.[1] USAF warfighters have long envisioned using increasingly autonomous unmanned aerial vehicles (UAV) to perform demanding missions that previously required either a human in a cockpit or remote human control of an unmanned system. The Air Force is now developing new operational concepts for teaming manned fighters and bombers with autonomous UAVs—called manned-unmanned teaming (MUM-T)—to perform strikes, counterair, electronic warfare, and other missions. The goal of MUM-T is to deliver a set of options that significantly enhance operational capabilities and capacity past what is available today with current systems and practices. The perceived lower enterprise mission cost of using unmanned technology also drives the concept. Given the scale of current and future challenges, successfully delivering MUM-T in alignment with these capability, capacity, and cost goals is imperative.

For MUM-T to work in the operational realm, it will be crucial for manned and unmanned aircraft to collaborate closely and in ways that are effective and trusted by human warfighters. The future battlespace will not be entirely all manned or unmanned—it will be a hybrid. Pragmatic reliability and dependability are key benchmarks for success. The captain on the flight line will be the ultimate arbiter of whether these new solutions are value-added.[2]

Developing a far deeper shared understanding between engineers and warfighters regarding how UAV autonomous technologies map to combat performance is critical to fielding a future force capable of large-scale MUM-T operations.

Developing a far deeper shared understanding between engineers and warfighters regarding how UAV autonomous technologies map to combat performance is critical to fielding a future force capable of large-scale MUM-T operations. As important as autonomous aircraft are to the Air Force's future force design, the software algorithms that underpin their behavior and performance are generally not well understood outside technical circles. Although the USAF's warfighters and acquisition professionals intuitively grasp the *potential* for autonomy and artificial intelligence to transform warfare, most lack in-depth *knowledge* of what is needed to make these algorithms combat viable. Instead, autonomy and artificial intelligence technologies are often treated as "pixie dust"—just sprinkle a little on top to solve hard problems and magically make weapon systems do things autonomously. It will take more than this cursory understanding to meet tomorrow's demands. Actors need to know the relative strengths and weaknesses of the given systems and the underlying factors driving these standings.

Blind faith in technology absent rigorous oversight and a clear implementation vector is insufficient to articulate specific requirements, right-size development programs, manage expectations, and rapidly field and iterate autonomous systems. Furthermore, the lack of understanding of autonomy generates serious miscommunication and mistrust between what the USAF's strategic planners envision, what its operational

The Value of an Autonomy Framework

The Air Force needs an autonomy framework for unmanned aircraft that brings clarity, coherence, and rigor to its pursuit of autonomous capabilities. The shared understanding between warfighters and engineers that this framework could facilitate would help focus developmental efforts, speed up the fielding of capability in high-return areas, and increase warfighter trust and adoption of autonomous teaming aircraft.

Such a framework should:

- Provide a consistent structure for the development of autonomy capabilities for unmanned aircraft.
- Engender greater fidelity in describing autonomous capabilities for CONOPS development.
- Create a basis for the rational and deliberate prioritization of autonomy-enabling technologies.
- Clarify the role of the human during autonomous aircraft operations.
- Establish a common reference point that spans the science and technology, acquisitions, operations, and policy-making communities.
- Empower senior leaders and policymakers to make informed tradeoffs between capabilities, risks, and costs.
- Encourage specificity and precision in language to reduce miscommunication and misunderstanding among stakeholders.

Ultimately, an autonomy framework for unmanned aircraft should facilitate better communications between warfighters and engineers, help them identify the most promising technologies for autonomous aircraft, and rapidly transition them to warfighting capabilities America's combatant commanders need.

warfighters need, and what aerospace engineers can deliver. All these challenges are a major barrier to the acceptance of autonomous technologies. If these barriers persist, DOD can look forward to delayed development timelines, broken acquisition programs, and even a failure to maintain an advantage in these technologies over America's strategic competitors. National defense professionals urgently need a common framework that explains and demystifies autonomous systems in ways that are inherently intuitive and enables them to clearly communicate across communities. This study's proposed framework for autonomy intends to help develop this common understanding and more effectively transition autonomous aircraft technologies from science projects to real-world combat capabilities that are trusted by warfighters.

Overview of a proposed autonomy framework

The autonomy framework proposed in this report is based on how human pilots think and operate. The framework serves two basic purposes: to facilitate warfighter understanding of autonomy and provide a model to facilitate the development of autonomous technologies. Basing this framework on how combat pilots think and operate in the battlespace will help them better understand *and explain* how autonomous aircraft should perform. Use of this framework should also increase warfighter trust and acceptance of autonomy. This will be a crucial step toward initially fielding and integrating autonomous UAV teammates into operational concepts and tactics, as well as identifying how maturing autonomy technology can continue to improve autonomous UAV capability over time.

The proposed autonomy framework has two major parts: a **“Warfighter View”** and an **“Engineer View.”** The Warfighter View is broken into three functional categories for autonomy called **Core**, **Mission**, and **Teaming,** which are based on the cognitive processes of human combat pilots during mission execution. Because these functional categories are modeled on combat pilots’ own mental and physical tasks, the framework intuitively maps autonomy algorithms and behaviors to human expectations for their performance. The framework also includes five levels of autonomy within the categories, with each ascending level representing an increased measure of autonomy. The Engineer View then uses the information from Warfighter View categories and their autonomy levels to guide the development of data, software, and hardware needed for future MUM-T operations. This part of the process should include affording engineers a basis to provide feedback to warfighters and program managers, explaining limitations or potential tradeoffs in the development of the software and hardware.

This framework is designed to provide a “language” that warfighters can use to describe their expectations for autonomous UAV behaviors and then explain them to technologists and aerospace engineers that design the algorithms and other elements of advanced unmanned systems. Warfighters and operational planners should not have to learn software programming to understand and trust autonomous capabilities on which they depend. This framework allows warfighters to articulate their expectations for autonomous system

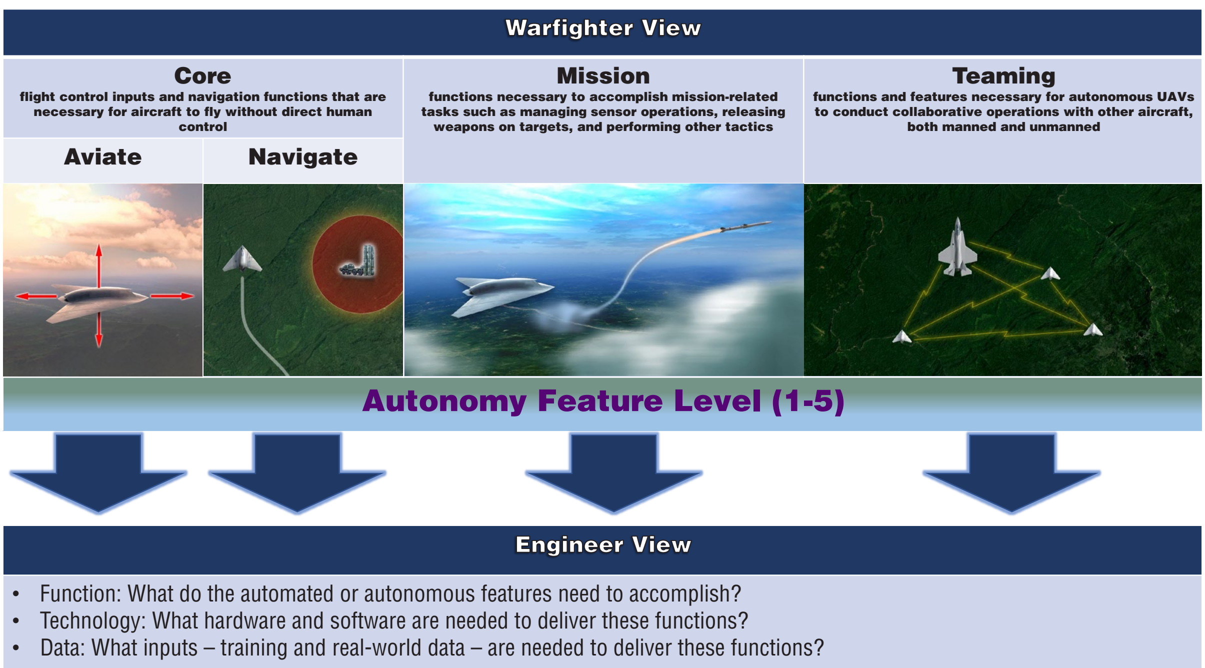

Figure 1. Overview of a two-part framework to improve warfighter understanding of autonomy and communicate their requirements to the developmental and acquisition communities.

Credit: Mitchell Institute, Heather Penney, Maj Christopher Olsen, Kamilla Gunzinger, and Zaur Eylanbekov behaviors in ways that are intuitive, measurable, and will help them clearly provide the information needed for the development of autonomous teaming aircraft to the engineers. In other words, modeling the categories of autonomy on how humans execute the complex and interwoven tasks of combat aviation operations will create a solid foundation for functionally engineering autonomous aircraft. In this way, the framework will help bridge the "valley of death" that often exists between the development of advanced autonomous technologies and the deployment of game-changing weapons systems.

Using and developing the framework to its fullest potential will demand that the AF/A5 staff, AF/A3 staff, major command (MAJCOM) operators, acquisition professionals, technologists, and industry maintain a tight and collaborative interaction throughout the requirements definition, acquisition, and development lifecycle.

No framework will be useful unless it is implemented. This Two-View Autonomy Framework for Unmanned Aircraft across the USAF enterprise should formally reside with the Deputy Chief of Staff for Strategy, Integration, and Requirements (AF/A5). The AF/A5 is responsible for defining requirements for new systems as part of the USAF's acquisition and development process, and as such it is optimally positioned to introduce and employ the framework in the development of new autonomous teaming aircraft (ATA). Yet, this framework cannot successfully move autonomy forward without the full participation of the operational community. Therefore, the Deputy Chief of Staff for Operations (AF/A3), Air Combat Command (ACC), and Global Strike Command (GSC) should champion the framework. The AF/A3 staff has operational experience and deep ties into the operational community, the Air Force Warfare Center, the Air Force Research Laboratory, other defense labs, and the acquisition community. ACC and GSC, as the initial and primary warfighter "user community," must also champion and participate in the use of the framework to develop autonomous systems. Using and developing the framework to its fullest potential will demand that the AF/A5 staff, AF/A3 staff, major command (MAJCOM) operators, acquisition professionals, technologists, and industry maintain a tight and collaborative interaction throughout the requirements definition, acquisition, and development lifecycle.

Background

Before discussing the framework that will help guide the next step in UAV development, it is important to understand what past and current remotely piloted aircraft (RPA) have achieved, as well as what future missions will demand of tomorrow's capabilities. Remotely piloted aircraft like the MQ-1 Predator and MQ-9 Reaper have transformed elements of warfare over the last two decades, but new missions and threat factors increasingly require autonomous aircraft that can operate independently of extended-range data links and do not incur large bandwidth or intensive manpower demands. If military commanders want next-generation options in the future decade, then serious development work needs to scale now.

Conducting a single persistent 24/7 RPA combat air patrol necessitates continuous, high bandwidth connectivity over long ranges and uses roughly 200 people for successful mission execution. A team of pilots and sensor operators, often located a continent away from an RPA's area of operations, is needed to control these uninhabited aircraft. Perhaps even more critically, these long distances impose time delays in an RPA's operational cycle. An RPA must transmit data from its sensors to its remote operators, who must assess the data, determine an appropriate action, and then transmit control signals back to the RPA. These operational characteristics will be significant, perhaps decisive, limitations in a conflict where China or Russia seeks to disrupt U.S. networks and datalinks—especially for aircraft operating forward in ahighly contested battlespace.

RPA currently in the Air Force inventory will continue to be a keystone to U.S. combat operations across the spectrum of conflict for the foreseeable future, with important and evolving roles in future warfare. In fact, the demand by combatant commanders for RPA like the MQ-9 Reaper has only continued to grow. Nonetheless, the need to increase enterprise capacity, operational effects, and resiliency in highly contested environments means that developing autonomous teaming aircraft is a strategic imperative.

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The first wave: RPA for dull, dirty, or dangerous missions

The ability to fly uninhabited aircraft, including UAVs, RPA, or "drones," has enabled the Air Force and other services to execute missions where human pilots have been a limitation. RPA have historically been used for missions characterized as dirty (such as radiological), dangerous, or dull (long duration operations). In the 1950s, remotely piloted B-17s flew through clouds to collect samples of radioactive fall-out created by nuclear weapon test shots. During the Vietnam conflict, the high-speed AQM-34L Firebee conducted low-level battle reconnaissance into threat areas and through bad weather deemed too risky for manned aircraft. Firebees used an inertial navigation system and a rudimentary autopilot to navigate and fly a fixed course without real-time pilot control inputs. In the late-1990s, the remotely piloted RQ-1A Predator conducted long-duration live-video surveillance of very specific points of interest in the Balkans—providing real-time situational awareness that was unprecedented. Commanders had previously been limited in their ability to conduct these dull, dirty, or dangerous missions with aircraft that needed a human pilot in the cockpit.

Figure 2. The AQM-34L Firebee "Tom Cat." Credit: U.S. Air Force Photo

The passage of time, intensive development, and operational experience in recent decades has exploded the value UAVs now offer, far past dull, dirty, and dangerous missions. Technologies such as live-video feeds, wide-bandwidth space-based data links, and machine-to-machine information exchange have expanded the range of missions RPA can perform and improved how they are integrated with manned combat operations. In addition to providing persistent intelligence, surveillance, and reconnaissance (ISR), armed RPA that can loiter for a long period of time in the battlespace can be used to directly attack fleeting targets while minimizing collateral damage. RPA also collaborate with manned aircraft, providing them with targeting information and even tasking combat aircraft similar to how fighters are tasked by a forward air controller. With a proven and operationally significant record in Iraq, Afghanistan, Libya, Syria, and other regions around the globe, RPA employment has been and will continue to be essential to U.S. and coalition combat operations.[3]

Limitations of today's RPA in a peer conflict

Current generation RPA have pioneered the ability to collaborate with manned aircraft with impressive results, but it is time to take this partnership to a new level. The contested battlespaces of the future will require that next-generation UAVs match many of the attributes of manned aircraft if they are to maximize their combat utility in teaming operations. Whether executing formation-based tactics or detached synchronized operations, future UAVs will need to have physical attributes to survive and be mission effective. These requirements include aerodynamic considerations like signature management, electrical power, processing, range, payload, and even speed and maneuverability. In addition to aerodynamic design, engineers must address the inherent lag between control inputs that are transmitted by pilots over datalinks from the other side of the globe and RPA responses to remote commands. Reducing lag times between control inputs, aircraft responses, and operator feedback now requires a forward-deployed pilot and low-latency line-of-sight datalinks. This lag time is not simply about the UAV's physical controls; this delay also affects the UAV's sensor and other mission systems. While remote pilots and operators are able to compensate for this in current operations, warfighters cannot execute future MUM-T operations in a highly dynamic and contested battlespace with such time delays.

In a spectrum-contested battlespace, the control datalinks RPA operations depend on may be degraded or even unavailable. These links present a valuable target for enemy kinetic and non-kinetic attacks because the mission effectiveness of RPA can be negated if their line-of-sight, satellite, and other long-range links are disrupted or denied. The RPA will "go stupid" and execute lost-link procedures such as flying a triangular pattern until nearing minimum fuel and returning to base. This is a well-known vulnerability, but not the only one. In 2009, Iraqi insurgents hacked into MQ-1 Predator feeds to monitor and exploit their operations.[4] While encryption was eventually installed to secure RPA control links and prevent adversary intelligence gathering, the long-range, high-bandwidth data links will remain critical vulnerabilities to RPA operations in any kind of contested battlespaces. Bottom line, while the rapid evolution of RPA in the past few decades has been incredible and the results exceeded the most optimistic expectations, the demands of highly contested battlespaces will require a major step in developing and fielding operational UAV capabilities. These enhanced capabilities must be focused on the ability to effectively team with high-performance manned aircraft in the manner and at the scale that a future peer conflict would require.

The next wave: MUM-T operations

Current RPA have proven unmanned aircraft can operate in cooperation with manned aircraft and provide additional mission-effective combat capacity. Examples include Gray Eagle RPA teaming with Apache AH-64E helicopters for hunter-killer operations, MQ-9s collaborating with Air Force or Navy fighters during sensor-shooter strikes, and MQ-9s sharing data with manned strike aircraft during an Air Force ABMS on-ramp demonstration.[5] The U.S. defense community needs to take this to the next level, but that requires new technology with high-performance attributes that can scale affordably. Secretary of the Air Force Frank Kendall touched upon this when he recently remarked that a new generation of unmanned platforms will be the key to giving the Air Force "the quantity we need at a reasonable cost."[6] Achieving this kind of effective mass in peer conflicts will require UAVs that are far less dependent on large numbers of supporting personnel and long-range datalinks compared to RPA. In short, highly resilient manned-unmanned teaming operations at scale will require the Air Force to shift from remotely *piloting* its unmanned aircraft to using human flight leads to *direct* the operations of UAVs that are increasingly autonomous.

Instead of being controlled by pilots and sensor operators half a world away, future autonomous teaming aircraft—ATAs—must be capable of flying, maneuvering, managing sensors, and executing missions without a human providing close control inputs. In command-and-control terms, this means humans will be tactically "on the loop" for ATA operations instead of "in the loop" as they are with RPA. Broadly conceived, unmanned ATAs will be wingmen to manned flight leads or mission commanders who monitor their autonomous operations and direct them only as necessary. Importantly humans will retain positive authority over these aircraft and will verify and exercise consent to any weapons employment. MUM-T operational concepts envision using a family of different UAVs that have a range of artificial intelligence to augment manned flight leads by providing additional sensors or weapons, replacing traditional wingmen, or executing detached mutual support taskings. With the ability to execute dynamic, responsive, and coordinated tactical maneuvers during either independent or teamed missions, ATAs can become true force multipliers.[7]

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Autonomous technologies are the key to MUM-T

Potential MUM-T use cases include forward sensing, electronic warfare, expanded weapons payload, suppression and destruction of enemy air defenses, and offensive/defensive counter-air escort, among

Autonomous Teaming Aircraft (ATA)

ATA are unmanned aircraft specifically designed to collaborate closely with manned aircraft to execute missions with human direction and oversight, but with minimal control inputs to decrease the workload demand on the human flight lead. These aircraft can be understood as wingman surrogates—able to tactically maneuver in a dynamic battlespace and contribute to mission execution, but still under the command and direction of a human.

others.[8] From a force design perspective, MUM-T autonomous aircraft will be a key to building the future Air Force. ATAs will increase the USAF's capacity to conduct precision strikes and create other meaningful operational effects while imposing additional targeting dilemmas on enemy air defenses. Ultimately, ATAs will enable aircrews to focus greater time and attention on more important, difficult, and demanding tasks, exploiting the strengths of human cognition and decision-making to achieve combat success in high-end peer conflicts. The perceived enterprise cost advantages of ATAs, and of course their ability to secure mission effects, are important factors driving investment in this area versus an entirely manned force.

The U.S. Air Force, other agencies in the Department of Defense, and the defense industry are engaged in multiple programs to develop autonomous functionality for existing and future UAV platforms.[9] The Air Force Research Lab (AFRL) Skyborg program aims to develop "full-mission autonomy" as part of its Low-Cost Attritable Aircraft Systems (LCAAS) concept to enable manned-unmanned teaming operations. Skyborg is not an aircraft but an open-system architecture of autonomous technologies that is intended to be broadly compatible with a range of different aircraft. Skyborg autonomy took flight in the spring of 2021 in both a Kratos Mako drone and a General Atomics RQ-20 Avenger.[10] Both aircraft autonomously stayed inside required airspace boundaries, responded to navigation commands, demonstrated coordinated maneuvering, and honored flight performance envelopes.

The Defense Advanced Research Projects Agency (DARPA) Air Combat Evolution (ACE) program has been pursuing the development of an AI capable of learning to maneuver in relation to a highly dynamic fighter aircraft. ACE's "Alpha Dogfight" virtual trials tested the AI against a human pilot in basic fighter maneuvers—dogfighting—in which the AI won all five engagements. The defense industry is also developing multiple designs capable of autonomous MUM-T operations. Lockheed Martin's Have Raider MUM-T demonstrator, Northrop Grumman's autonomous Model 437 aircraft, and Boeing's Loyal Wingman UAV, in addition to projects by Kratos and General Atomics-ASI, all promise to deliver new AI-enabled ATAs that will help the USAF maintain its technological edge over peer adversaries.

The Need for an Autonomy Framework to Guide Autonomous Systems Development

As promising as the number of MUM-T development initiatives may be, gaps between warfighter expectations and what autonomous technologies will and will not provide emerge when the discussion goes deeper than the headlines. This distance must be closed given the need to rapidly field new capabilities with limited budgets, tight timelines, and a burgeoning enemy threat. It is crucial to ensure commanders, operational actors, and technologists speak the same language. Requirements must be properly identified and met, and as effectively and efficiently as possible. DOD simply cannot waste vast sums of money and significant time on pathways that do not speak to pragmatic warfighting requirements. This is an "on time, on target" moment in history. If warfighters cannot trust that these autonomous teaming aircraft will behave as they expect or adhere to certain mission principles, then they will resist fully adopting and integrating this important capability into combat operations.

Automation versus Machine Learning

Automation is governed by deterministic rulesets. Much like an autopilot, which must be specifically programmed, automation is highly scripted and only able to respond to pre-defined variables and decision points. These limitations can impose a significant burden on the user to monitor, control, or override the automation.

Machine-learning, or artificial intelligence, is based on self-optimizing algorithms that rely on data and training to continually improve the system's performance. Because machine learning is not scripted or wholly predictable like automation, it can be more adaptive, innovative, and surprising.

These characteristics make machine learning more relevant for dynamic and unpredictable environments, while simultaneously posing the risk that machine learning may be less reliable than automation in providing the desired or expected behavior.

Autonomy in tactical teaming operations is a far more complex technological problem than an aircraft's ability to maintain its speed, altitude, attitude, and flight path without a human in direct control. At a basic level, it is important to understand the difference between automation and autonomy. Automation is independent behavior that results from rules-based programming—it is rigid and predictable, like an autopilot. Autonomy, on the other hand, is far more flexible and dynamic because it is based on machine learning algorithms that are trained by data. Automation and autonomy are not the same, even though they are often used interchangeably. When considering how ATA should behave in the battlespace, key questions emerge: What should autonomy do, and "how much" autonomy is needed to accomplish a particular mission? These questions become more difficult to resolve as one delves further into the tactical execution of MUM-T operations. How should a UAV's autonomous "brain" respond to rapidly changing battlespace conditions? What types and volume of data are required to implement different MUM-T operations such as strikes, close air support, or counterair tasks? What technologies (e.g., algorithms, sensors, interfaces, etc.) need to be matured for ATA to conduct these operations? And how do the answers to these questions change as broader mission requirements

What is Autonomy?

There is no widely accepted common definition of autonomy. While one might intuitively grasp autonomy in the MUM-T application—the "you know it when you see it" standard—the lack of a clear and shared definition of autonomy leads to a breakdown of understanding between warfighters and engineers. They simply talk past each other. For this paper, autonomy will be defined as the system's or category's ability to self-direct in an adaptive manner. The intent behind this definition is to capture the level of burden the teammate imposes on its human flight lead, as well as the ability of the teammate to adaptively respond on its own to unexpected circumstances. Lower levels of autonomy, for example, would impose a greater burden on the human flight lead to control, direct, or choose courses of action for the teammate. Higher levels of autonomy, by contrast, would allow the human to provide the teammate with command intent of outcome and then monitor and consent to the teammate's actions.

and unmanned operational concepts evolve? All of these questions point to the most important question, which gets to the heart of the warfighter trust issue: How should ATAs "think" about their missions? Clearly, answering *this* question is key to developing operational autonomous unmanned teammates that warfighters can trust to perform operations critical to mission success in highly dynamic, high-end combat.

Attempting to answer these questions reveals there are communication breakdowns and a general lack of shared understanding about AI-enabled autonomous UAVs across USAF requirements, acquisition, planning, and operational communities. This confusion reflects the reality that no structure exists upon which to rigorously and methodically base the description or development of autonomous capabilities. In fact, the main architecture used for most UAV development today simply reflects the weight class and altitude of the given aircraft. Tomorrow's challenges demand a totally different framework that speaks to current challenges and focus areas.

Warfighters presently do not have a sufficient comprehension of what autonomy is to determine what kind of and how much autonomy is needed for these systems to achieve desired behaviors. Engineers, on the other hand, often do not fully understand how to decompose warfighter functional performance requirements in ways that enable them to rapidly field effective systems. Crucially, the connections between desired warfighter effects and the technological pathways to implement them are shaky and ill-defined. Consequently, the associated visions, strategies, roadmaps, operational concepts, programs, and myriad research and development efforts for ATAs have not come together in a clear and coherent way. In short, there does not seem to be a commonly understood framework that can help the Air Force to understand autonomous technologies and help to guide the enterprise from where it is today to where it needs to be in the future.

DOD's current UAV framework does not address autonomy

As mentioned, the UAV framework now used by DOD and the Air Force establishes five categories for unmanned aircraft. Under this categorization scheme, as shown in the figure from Joint Publication 3-30, unmanned aircraft are assigned to groups primarily based on their gross takeoff weights, although their normal operating altitudes and airspeeds are also considered.[11] While useful in some regards, these metrics are wholly disconnected from the challenges and opportunities of autonomous UAVs.

In general, aircraft gross takeoff weight increases with UAV group number, except for groups 4 and 5, where the primary discriminator is normal operating altitude. The weight limits and operating altitudes are closely tied to the Federal Aviation Administration (FAA) unmanned aircraft categories and airspace regulations.[12] For example, the maximum weight of a group 2 aircraft (55 lbs.) is also the FAA maximum weight for small unmanned aerial systems.[13] Similarly, the normal operating altitude limit for a group 1 aircraft of 1,200 feet above ground level corresponds to the upper limit of class G uncontrolled airspace for flights that are not under the authority or responsibility of air traffic control. For groups 3–5, aircraft with a maximum gross takeoff weight of 1,320 pounds mirrors the current FAA weight limit for general aviation light sport aircraft. Aircraft heavier than 1,320 pounds are regulated under the FAA's normal/utility aircraft category. UAVs that operate above 18,000 feet mean sea level, where all aircraft must operate under instrument flight rules according to the FAA, are categorized as Group 5.[14] It is clear, then, that DOD's "Unmanned Aircraft Systems Categorization" is primarily based on measures associated with operating unmanned aircraft in uncontested civil airspace.

Unmanned Aircraft Systems Categorization Chart

UA Category	Maximum Gross Takeoff Weight (lbs)	Normal Operating Altitude (ft)	Speed (KIAS)	Representative UAS
Group 1	0-20	< 1200 AGL	100 kts	WASP III, TACMAV RQ-14A/B, Buster, Nighthawk, RQ-11B, FPASS, RQ16A, Pointer, Aqua/Terra Puma
Group 2	21-55	< 3500 AGL	< 250	ScanEagle, Silver Fox, Aerosonde
Group 3	< 1320	< 18,000 MSL	< 250	RQ-7B Shadow, RQ-15 Neptune, XPV-1 Tern, XPV-2 Mako
Group 4	> 1320		Any Airspeed	MQ-5B Hunter, MQ-8B Fire Scout, MQ-1C Gray Eagle, MQ-1A/B/C Predator
Group 5	> 1320	> 18,000 MSL	Any Airspeed	MQ-9 Reaper, RQ-4 Global Hawk, RQ-4N Triton

Figure 3. The unmanned aircraft systems categorization chart from Joint Publication 3-30 organizes UAVs into five groups that are primarily based on UAV weight. KIAS is knots indicated airspeed, AGL is above ground level, and MSL is mean sea level.

Credit: Joint Publication 3-30 as of July 2019

While airspace integration is important to facilitating RPA operations in the national airspace, this classification system is not useful or appropriate for the development of autonomous aircraft, MUM-T operational concepts, or prioritizing their associated research and development efforts. Plus, it does not address the potential roles or missions for autonomous aircraft or shed light on the particular traits and underlying technologies that set autonomous aircraft apart from their remotely piloted or manned cousins. This is why a complementary framework to categorize UAV autonomy could help the Air Force and DOD to move beyond RPA that are simply adjuncts to manned aircraft to increasingly autonomous manned-unmanned teammates.

A starting point: Inspiration from the automotive industry

The best-known and perhaps most advanced autonomous vehicle framework is the Society of Automotive Engineers' (SAE) "Levels of Driving Automation."[15] The model affords many elements that could prove useful to military UAVs, but combat requirements also drive unique realities that will demand a distinct construct.

The SAE framework defines six levels of driving automation—from no automation (level 0) to full automation level 5)—for automated vehicles (AVs). At level 5, vehicles with full automation require zero input from a human driver. The SAE graphic in Figure 4 helps consumers understand the spectrum of automated driving features that are available today or anticipated in the future.

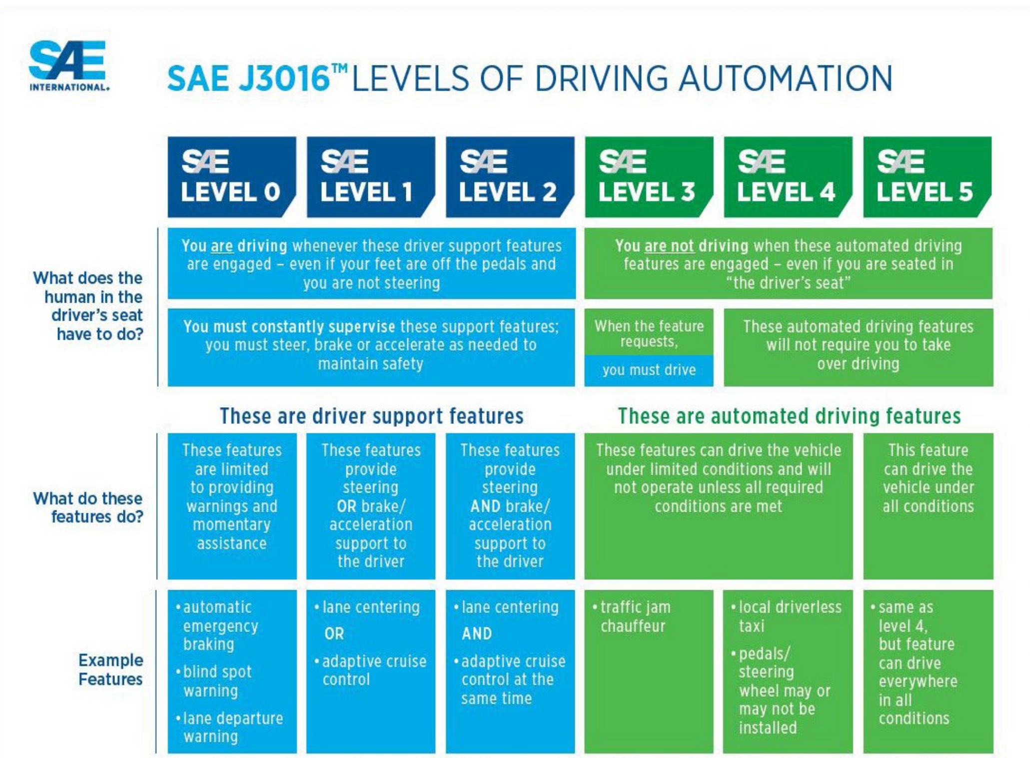

Figure 4. A graphic produced by the Society of Automotive Engineers (SAE) helps consumers understand the "levels of driving automation."

Credit: SAE International

SAE's vehicle taxonomy has several useful characteristics that could apply to a UAV autonomy framework for the Air Force. Foremost, each level of driving automation explicitly distinguishes between what an automated feature can perform and the tasks a human driver must do. By assigning automation levels to the two subcategories of "driver support features" and "automated driving features," the framework clarifies the gradual transition from human control to autonomous control. Furthermore, it explains the performance thresholds that must be met for the different driving automation features and the limitations of which human drivers should be aware. Finally, the SAE framework provides concrete examples of what automation features do at each level for added clarity.

A useful autonomy framework for Air Force applications must be tailored to address the realities of aircraft flight, navigation, mission requirements, and teaming—all in a complex, ever-changing, and contested military operating environment.

The SAE's established standard for driving automation is a useful starting point for an Air Force autonomy framework for unmanned aircraft, although it is not a perfect template for military operations. Notably, the driving automation features for personal vehicles have a relatively narrow purpose—safely navigating a vehicle from its origin to its destination. Moreover, operators—human or autonomous—of ground vehicles that travel on highways benefit from road markings and signage, as well as laws and well-established customs of the road. Furthermore, self-driving cars do not collaborate with other cars. By contrast, unmanned aircraft in military applications must not only be prepared to navigate through a complex, dynamic, and potentially denied, degraded, intermittent, or limited communication battlespace, but also execute mission functions in concert with other human and machine teammates. Therefore, a useful autonomy framework for Air Force applications must be tailored to address the realities of aircraft flight, navigation, mission requirements, and teaming—all in a complex, ever-changing, and contested military operating environment.

A Proposed Autonomy Framework for Unmanned Aircraft

The Mitchell Institute proposes an autonomy framework based on this analysis comprising two parts called the **Warfighter View** and the **Engineer View**. The term "view" is used because they are describing two different perspectives that are crucial to creating a common understanding of the degree of autonomy needed to deliver ATA capabilities. Together, these two views act as the connective tissue or translator between warfighters and engineers. The two-view framework intends to resolve disconnects between the warfighters who require autonomous UAVs to perform certain tasks and the aerospace engineers who develop UAV system designs, algorithms, and other inputs.

Framework overview

The **Warfighter View** in the proposed autonomy framework has three major categories, each of which are subdivided into five levels of autonomy. The categories **Core**, **Mission**, and **Teaming** mirror pilot cognitive tasks and are intended to be intuitive to warfighters, helping them to express their requirements for how autonomous systems should perform. The Core autonomy category encompasses flight control inputs and navigation functions that are necessary for aircraft to fly without direct human control. The Mission category includes functions necessary to accomplish mission-related tasks such as managing sensor operations, releasing weapons on targets, and performing other tactics. Teaming covers functions and features necessary for autonomous UAVs to conduct collaborative operations with other aircraft, both manned and unmanned. Each of these three major categories is then subdivided into five autonomy levels. Level 1 represents tasks that are performed with little automation, and level 5 includes actions unmanned aircraft perform fully autonomously.

The second part of the framework is the **Engineer View**. The Engineer View represents a functional decomposition of the Warfighter View, breaking the defined category and level down into functions, technologies, and data. This clarity of focus enables engineers to map and prioritize their developmental efforts to desired vehicle attributes and behaviors. While the warfighter is concerned with macro-level mission execution, operational behaviors, and the role of humans in operations, the engineer is concerned with the underlying functions, hardware, software, and data necessary to build an autonomous system that meets the warfighter's needs. In other words, the Engineer View enables aerospace engineers and technologists to deconstruct warfighter requirements into the underlying technologies and foundational autonomy elements.

Together, these two views act as the connective tissue and translator between warfighters and engineers. It is important to note that this framework is not intended to be a specification or a standard. This is similar to the SAE's automated driving framework, which says the intended goal of the framework is to be "descriptive and informative rather than normative."[16] In that vein, the primary purpose of the proposed two-view autonomy framework is to enable warfighters and aerospace engineers to clearly communicate and exchange ideas and requirements for autonomous unmanned aircraft in a structured and consistent way.

Part 1 of the Autonomy Framework: The Warfighter View

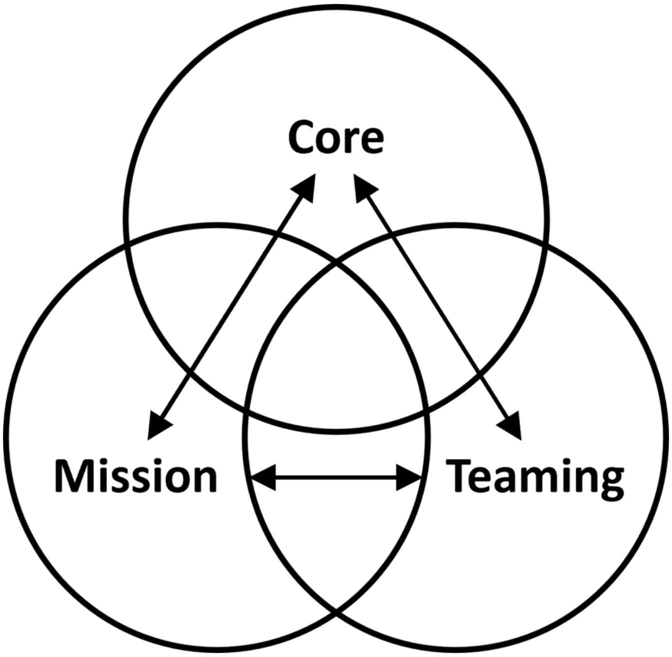

Figure 5. The auto-features and functions that belong to the Core, Mission, and Teaming categories frequently interact and overlap to produce the desired operational behaviors.

Credit: Heather Penney

The Warfighter View was developed by decomposing how pilots perform cognitive and functional tasks during combat operations. Basing this framework on these human pilot inputs will help them to intuitively understand the framework and accurately represent how they think and operate in the battlespace. It will also increase their understanding of how aircraft with different levels of autonomy will behave and, importantly, the trust they place in these novel combat systems.

The Warfighter View's three Core, Mission, and Teaming categories for autonomous functions are modeled on the cognitive processes combat pilots use when executing operational missions. These three categories do not represent or imply that separate and isolated packages of hardware and software are needed for each. While auto-features and functions sometimes operate independently and for their own purposes, there are natural interactions and dependencies between them. Pilot decisions and actions often are the result of complex tradeoffs between each category while simultaneously making tradeoffs across different timescales. A combat pilot is constantly weighing courses of action that are constrained by what has happened in the past, what the present demands, and what the future may possibly require. Indeed, it is crucial for warfighters, aerospace engineers, and technologists to work together to fully map out complex interactions between these categories as they develop and mature autonomous teammates that meet warfighter expectations and mission demands.

The Core category: Aviate and Navigate tasks

The Core category encompasses all the automatic actions—auto-features—unmanned aircraft perform that result in behaviors that are common to all flying aircraft, regardless of role or mission. This category is broken into Aviate and Navigate responsibilities that are intended to capture the basic and advanced flight skills a pilot learns in undergraduate pilot training and follow-on flight training in their operational weapon system.

Core Aviate refers to all automatic features and functions performed by an aircraft's systems to fly the aircraft through its entire performance envelope and during all phases of flight. The core responsibility for pilots is to always control their aircraft, whether managing an autopilot, using digital flight control technologies, or manually manipulating controls that move aircraft flight control surfaces. At a basic level, one can consider this the "stick and rudder" part of operating aircraft—making continuous flight control inputs that cause specific aircraft responses within very short feedback loops. In other words, these are the basic and advanced aircraft and flight control skills that any combat pilot learns—how to take off, climb, level off, turn, descend, accelerate or decelerate, approach and land, and so forth. More tactically, one might think of flying at high angles of attack, setting the lift vector, establishing roll rates, pulling Gs, or any combination of actions required to maneuver an aircraft. While there are commonalities in the laws of aerodynamics, each aircraft will have unique attributes associated with its design.

Pilots must also decide how to trade off an aircraft's speed, altitude, and thrust with flight maneuvers that will position the aircraft in time and space to perform specific actions. These maneuvers must be in relation to conditions in the physical world, including weather and terrain features, runway locations, and the aircraft's available fuel, as well as the battlespace environment. Moreover, combat pilots must constantly make these short- and long-term decisions and tradeoffs informed by their operational mission objectives. Finally, the Aviate subcategory includes preventing and handling flight-related contingencies and emergencies such as wing stalls, engine failures, or battle damage, like the loss of one or more control surfaces.

Core Navigate, in simple terms, tells Aviate where an aircraft should go to accomplish a mission. Navigate may be further decomposed into absolute or relative functions. "Absolute Navigation" covers route planning and determining a course for an aircraft to fly between multiple fixed locations in space, to avoid terrain and no-fly zones, or to remain within permissible airspace boundaries. "Relative Navigation" functions are generally concerned with an aircraft's relative position and vector with respect to the air environment, other aircraft, and the battlespace, not specific geographic locations. Relative Navigation functions include avoiding bad weather and mid-air collisions, conducting aerial refueling, and flying in formation with other aircraft. More tactically, Relative Navigation functions can also include executing established tactics, techniques, and procedures; maneuvering to engage dynamic targets; avoiding threats; and taking other offensive or defensive actions.

Functions within these two subcategories are tightly coupled within the Core. Navigate could loosely be considered the "brains" of Core, and Aviate functions are the "muscles" of Core. At times Aviate may limit or constrain Navigate options. For example, if an aircraft is low on energy—a combination of speed and altitude—it may be unable to execute an immediate maneuver to position itself to attack a moving aerial target. In this case, information from Aviate functions would constrain an aircraft's Navigate options and require other actions for an aircraft to regain the energy required to engage a target.

The Core category probably benefits the most from the automatic performance features that are based on mature technologies with a proven record of operational success found on existing aircraft. Digital flight control systems, like those found on the F-16, F-22, and F-35, might be considered early examples of Core Aviate capabilities. These systems can already schedule aircraft controls based on pilot inputs, information from aircraft speed and altitude sensors, and aircraft energy states. Many modern passenger airliners can fly pre-programmed flight profiles with minimal intervention from the pilots, to include terrain and mid-air collision avoidance.[17] These modern capabilities include more advanced Aviate elements, such as auto-throttles and auto-braking. Many of these commercial aviation and navigation automation technologies provide a solid base on which to develop Core auto-features for military UAVs. While a commercial airliner flying through well-controlled and friendly airspace is a far cry from an unmanned aircraft facing multiple challenges in the modern battlespace, there still exists a rich collection of mature Core automatic technologies that can be drawn on to develop future autonomous combat aircraft.

The Mission category: Adding military value

Combat pilots must also maneuver their aircraft, manage their sensors, and effectively employ weapons and other systems to achieve their mission objectives. These Mission responsibilities are what combat pilots first learn in their formal weapon system training and then hone as they go through additional qualification and upgrade training. These include basic formation and maneuvering skills, mutual support and protection, sensor management responsibilities, and targeting contracts. The Mission category also includes higher-order functions such as a pilot's ability to properly interpret the battlespace, recall past mission events, assess the current tactical scenario, project possible futures, and then direct their aircraft formation and larger mission packages to execute actions to achieve mission success. More simply said, combat pilots must build accurate situational awareness over time to make tactical decisions and take actions. The Mission category also includes decision-making, risk management, optimizing sensor management, information sharing, situational awareness, tactical maneuvering, and weapons employment to successfully achieve the mission objective.[18] For ATAs, Mission functions should be tailored to achieve specific desired effects for Intelligence, Surveillance, and Reconnaissance (ISR); Suppression of Enemy Air Defense (SEAD); or Offensive Counter Air (OCA) missions—or any of the other missions for which the Air Force is responsible.

For ATAs, Mission functions should be tailored to achieve specific desired effects for ISR, SEAD, or OCA missions—or any of the other missions for which the Air Force is responsible.

Like Core functions, Mission is a complex category of functions that span multiple iterative temporal loops that inform and drive each other. Different mission sets have different objectives, and the Mission category interacts with Core and Teaming functions to achieve desired operational outcomes. For example, Mission requirements drive Core functions that position an aircraft and manage its hardware and software in ways that will optimize the employment of its different sensors, electronic warfare (EW) systems, guns, weapon payloads, and other onboard systems to achieve mission success. For example, Mission may recognize that a sensor's azimuth of stare is washing out its imagery and then direct Core to change the position of an aircraft and its sensors to achieve a better view of a target. Similarly, Mission would overlap with Core when selecting an aircraft engagement maneuver that will preserve aircraft energy for follow-on maneuvering or cash it all in to achieve a firing solution on a target. Mission also interacts with Teaming for operations that require information sharing, formation and maneuvering, or cooperation with other entities in the battlespace.

The Teaming category: Collaborate to dominate

Combat pilots rarely execute their mission alone, and Teaming is crucial to achieving mission objectives. The value of Teaming from a warfighting perspective goes far beyond what pilots experience when they first learn to fly in formation with other aircraft. Teaming encompasses all elements of tactics and mission integration in modern combat operations—warfighters must fight as part of a large and often multi-domain force. Like the framework's other categories, mission timing and scale are critical elements to success. Coordinating, integrating, and synchronizing individual actions across time and with all mission partners is essential to achieving desired operational effects. Teaming functions include formation flying, maneuvering as part of a team, information sharing with external entities and within aircraft formations, and synchronizing the effects multiple teammates create in the battlespace.

More specifically, the Teaming category covers **behaviors**, **auto-features**, and **functions** that facilitate operational collaboration between and among unmanned aircraft, manned aircraft, off-board information systems, command and control entities, and other players in the battlespace. Teaming is largely dependent on the framework's Mission functions because Mission defines the types and nature of Teaming actions that an autonomous aircraft would execute automatically (auto-features). For example, the types of tactical formation and maneuvering in a particular Teaming auto-feature would be dependent on the assigned mission. An autonomous aircraft performing as an air-to-air missile truck during an offensive counterair sweep scenario would have specific contractual formation responsibilities to its manned

How Unmanned System Behaviors, Auto-features, and Functions Interact in the Proposed Framework

A pilot leading a manned-unmanned aircraft team must understand how their unmanned systems will behave during missions. For the purposes of the proposed framework, unmanned system behaviors are generalized actions or outcomes that can be observed, experienced, or used by a warfighter. They are also the consequence of how an unmanned aircraft's auto-features interact within and across the framework's Core, Mission, and Teaming categories. Like behaviors, auto-features are actions or outcomes. They are also discreet categorized subsets of a desired behavior. Functions are the technologies and software that are required to provide an auto-feature that the flight lead experiences as a behavior.

For example, adaptive cruise control is an auto-feature of many vehicles today. Drivers experience the behaviors of vehicle acceleration or deceleration to maintain a set distance within a given set of parameters when they enable the auto-feature of adaptive cruise control. Functions that enable this auto-feature could include range sensing, road friction sensing, brake control, measurement of closure rates, and so forth. Adaptive cruise control might be combined with other auto-features, such as navigation, to enable the behavior of autonomous driving.

In this sense, functions are the technological ingredients that, when combined, create an auto-feature. Similarly, auto-features can be combined in different ways within the Core, Mission, and Teaming categories to contribute to behavioral outcomes.

Autonomy Levels	Warfighter View			
	Core		Mission	Teaming
	Aviate	Navigate		
				
5	Fully Autonomous (AI | Machine Learning) – Minimal Human Command and Supervision			
4	Semi Autonomous (AI | Machine Learning) – Moderate Human Direction and Supervision			
3	Full Automation (Deterministic) – Moderate Human Supervision and Control by Exception			
2	Partial Automation (Deterministic) – Moderate Human Direct Control and Supervision			
1	Low Automation (Deterministic) – Significant Human Direct Control and Supervision			

Figure 6. Warfighter View: The autonomy categories and levels are used together in the warfighter view to form a rubric for describing the operational behavior and attributes of unmanned aircraft.

Credit: Mitchell Institute, Heather Penney, Maj Christopher Olsen, Kamilla Gunzinger, and Zaur Eylanbekov

flight lead. In this case, Core interacts with Teaming to automatically maintain the ATA's position (station-keeping) relative to its flight lead. Teaming provides Core with information of the ATA's desired flight trajectory and formation, which Core then uses to schedule flight control changes to deconflict and maintain the autonomous aircraft's position as the manned-unmanned team performs dynamic maneuvers. Other Teaming auto-features during a sortie like this might include updating fuel and weapons status, threat notification, conducting defensive maneuvers to protect the manned flight lead, or sharing information with entities outside the formation. Teaming might enable more fluid roles and responsibilities for formations of autonomous unmanned aircraft like swarms, such as shifting lead aircraft and mission duties depending on the swarm status and battlespace conditions.

Mission synchronization is a crucial element of Teaming auto-features. Autonomous aircraft must do more than simply transition from phases of a flight, like from ground operations to take off and climb out. In short, teaming can provide a "smart wingman" that recognizes the different phases of an operational mission and respond appropriately to contingencies in order to execute their combat responsibilities. Furthermore, autonomous aircraft performing independent support roles in missions like electronic warfare or suppression of enemy air defenses must be aware of the battlespace even when things don't go as planned. Interacting with Mission and Core to adapt to the unforeseen threats, unplanned contingencies, emergencies, and other chaotic events in contested battlespaces will be crucial to effective Teaming.

Five levels of human engagement: From automation to autonomy

The proposed framework has three levels of automation and two levels of autonomy in each of the three Warfighter View categories. This is similar to the SAE model that breaks levels of autonomy into human-driven actions in levels 1–3, which are largely automated and require some degree of human direction, and machine-driven actions in levels 4–5. Using these multiple levels will help aerospace engineers, technologists, and warfighters to describe and understand with greater precision and granularity what unmanned aircraft can and cannot do. In order of increased decision-making capability, level 1 is Low Automation, level 2 is Partial Automation, and level 3 is Full Automation. The next step up the cognitive ladder is level 4, Semi-autonomous, and level 5 is considered fully Autonomous.[19]

It is important to define what automation and autonomy mean. Automation is an action or set of actions that are performed according to predetermined rulesets when commanded by a user. A basic autopilot that maintains an aircraft at a specific altitude when activated by a pilot is a classic example of automation. The scope of the autopilot's decision-making is limited to determining how it should move an aircraft's control surfaces to maintain a desired altitude, but it will not, for example, decide on its own to change altitude to avoid an oncoming aircraft.

Autonomy, on the other hand, requires greater decision-making capacity. Autonomy transforms inputs to outputs according to a more general set of rules by drawing on a deep stack of inter-connected decision-making algorithms fed by volumes of data from multiple sources. Consider the autopilot example. Given input on a range of permissible altitudes and control actions, an autopilot enhanced with a high level of autonomy could decide what altitude the aircraft should fly based on factors such as weather, fuel efficiency requirements, teammate activities, or an impending collision. It could also make inputs to other systems that determine appropriate speeds for the aircraft based on mission needs and how to navigate to specific locations like weapon release points, as well as perform other tasks with minimal or no human control depending on their level of autonomy.

Although not a perfect comparison, one might liken automation to the abilities of a new wingman and autonomy to those of a highly experienced wingman. The new wingman largely flies formations and executes tactics and mission duties based on rote rules and rigid contracts. They do not have the ability to respond to unexpected inputs effectively and creatively, and they require much closer supervision and direction from the flight lead. This new wingman cannot cope with surprises or events that do not fit into the specific tactics they have been taught, and they may not even be able to recognize errors or surprises. The experienced wingman, on the other hand, still flies the standard formations and tactics, but they are capable of executing more complex and responsive tactics with greater independence and adaptation. Furthermore, their experience allows them to take on more expanded mission duties, and their enhanced situational awareness and judgment enable them to contribute to the collective decision-making of the flight. The experienced wingman requires less supervision from the flight lead, and they may even be able to execute certain tactics on their own or with detached mutual support, making the flight even more mission effective.

The natural question is, what is the difference between level 3 Full Automation and level 4 Semi-autonomous? Understanding this is important because the transition between levels 3 and 4 is the threshold where the preponderance of decision-making and control shifts from a human to a machine. Level 3 behaviors, auto-features, and other functions are brittle, meaning they operate within a more limited set of conditions. If the level 3 system drifts outside of its narrow envelope, it will either cease to function or no longer function as intended. In this case, a human operator would need to either take control or return the system to a state where its automation can once again function. A level 4 Semi-autonomous system, on the other hand, would remain stable within a wider envelope of operating conditions and possibly require fewer human interventions.

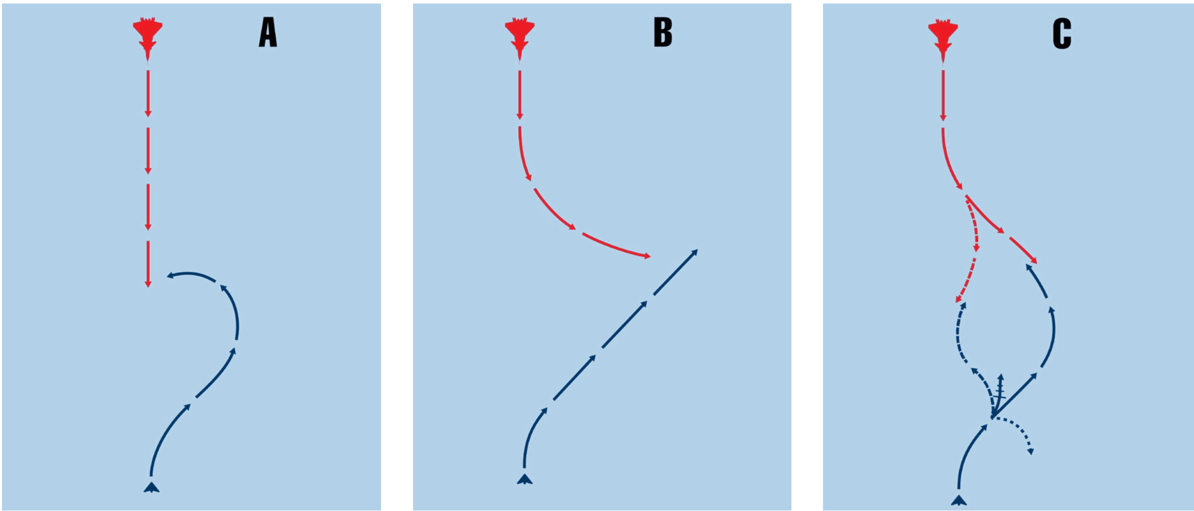

Figure 7. Single-Side Offset. Image A is depiction of a text-book single-side offset, where the ATA is offsetting the adversary so that it can gain turning room for a stern conversion intercept. In Image B, the deterministic programming of the teammate leaves it unable to adapt to the adversary's turn in. Once the adversary exceeds certain parameters, the ATA "goes stupid," driving straight and giving the adversary the intercept opportunity. In Image C, the autonomous teammate has the ability to adapt to the initial turn-in of the adversary and any other follow-on maneuvers.

Credit: Mitchell Institute, Heather Penney and Zaur Eylanbekov

For example, if a target maneuvered to change the intercept angle for a level 3 system, the teammate would not be able to complete the stern conversion because the new angle presented by the adversary maneuvers now exceeds its predetermined turn programming. In essence, the problem presented by the target exceeds the UAV's ability to solve. A level 4 Semi-autonomous system, on the other hand, would recognize the new problem and would take action to return the situation to a state inside the desired geometry by starting the turn early, using vertical turning room to achieve the angular alignment within the desired range, or even choosing a new tactic such as a high-aspect merge.

Determinism is the next differentiator between level 3 and level 4 behaviors and functions. Level 3 systems are deterministic and rules-based, meaning the same input always results in the same output.[20] Systems at levels 4 and 5 are non-deterministic. They could use underlying algorithms that employ stochastic (that is, probabilistic) methods, so level 4 and 5 systems may respond differently to the same inputs at different times. They may use machine learning algorithms that either learn in real-time or are periodically retrained to change how they behave. Non-deterministic behavior may also be the result of complex interactions of dozens of deterministic processes that are fed by hundreds of environmental and system state variables. In this case, a system may be technically but not practically deterministic, similar to a football bouncing down a field. If one knows the football's exact geometry, shape, speed, direction, complete knowledge of external conditions such as the contour of the football field, wind, and so on, then the motion of the ball might be predictable. In reality, there are too many variables and too many complex interactions between the football and its environment, so its movement is virtually impossible to predict. This makes the ball effectively non-deterministic. Anyone who has watched football players scramble after a kickoff, punt, or fumble can relate.

The final differentiator is scripted versus unscripted behavior. Full Automation, when operating within its prescribed limits, allow humans to assume a supervisory role. Which tasks to perform and in what order, however, are still dictated by the human. Anyone familiar with advanced flight management systems, autopilots, and auto-throttles understands this level of automation. From takeoff, climb, enroute, descent, and approach to landing, the aircraft performs its assigned tasks exactly as prescribed by the human. Level 4 and 5 autonomous systems, on the other hand, act in an unscripted way. Humans may still dictate which tasks the aircraft performs; however, the machine decides the order and manner of their execution. Some tasks may not be performed at all. The machine will decide based on its perception of the environment, its own internal state (e.g., how much fuel is left), or even the activities of its teammates. Thus, the behavior of a semi-autonomous or autonomous system is logical but not always predictable.

The next question is a natural extension of the first: What is the difference between level 4 Semi-autonomous and level 5 Autonomous? The defining trait that separates these levels is the robustness of an unmanned system's ability to manage all unanticipated things that may occur during a mission. These contingencies could result from both internal and external sources. Examples of internal contingencies are the loss of an engine or failure of a payload. External contingencies may be the presence of a threat the system cannot identify or teammates that act in ways the machine was not programmed or trained to deal with. When confronted with contingencies such as these, a level 4 system will either rely on its limited ability for self-diagnosis—such as a decision tree or "if-then" checklist—or require human intervention to resolve the problem. A level 5 system, on the other hand, will be equipped with a "soft decision tree" capable of sufficient self-diagnosis to simulate the higher-level cognitive functions a pilot would normally make. This gives the machine the ability to determine the best course of action on its own. This does not imply that humans "lose control" over level 5 systems. Instead, the autonomous aircraft can alert its manned "flight lead" about the contingency and provide a pre-packaged course of action for approval or adjustment.

A level of autonomy is assigned for each of the Core, Mission, and Teaming autonomy categories based on the specific behavioral criteria an aircraft must exhibit. Aircraft behavior at any given time is driven by the collection of engaged auto-features, which may change over the course of a mission. This approach provides sufficient granularity to conduct a useful operational assessment of a platform's autonomy and define the role of the human while remaining at a high enough level to avoid getting bogged down in minutia. The following paragraphs provide examples of low-end and high-end autonomy for each row of the autonomy categories described in Figure 6.

- **Core Aviate**. Aircraft digital flight control systems and digital electronic engine controls are two common examples of low-end autonomy for Aviate. At the low end of autonomy, a human pilot still actuates an aircraft's stick and throttle. Instead of manually controlling an aircraft's attitude and engines, these inputs are routed through a computer that interprets the pilot's actions as a desired outcome and then independently changes the aircraft's flight controls and engine thrust. At the high end of autonomy, the aircraft is capable of independently maneuvering anywhere within its performance envelope to meet navigational needs or as required by outputs from Mission or Teaming.

- **Core Navigate**. Navigation with low automation requires a human to perform traditional flight planning to decide on a route that meets mission requirements while avoiding threats and obstacles and obeying all boundary restrictions. The pilot then programs a flight route into the aircraft's mission system. Highly autonomous navigation ingests all pertinent external and relative data and plots an appropriate route dynamically, adjusting as needed with the physical environment, battlespace, and inputs from Mission and Teaming.
- **Mission**. An example of an electro-optical (EO) sensor platform with low Mission automation would require a human operator to manually search the field of view for a target, aim the camera, and so on. While the human operator would be manually controlling the EO sensor, automation might control its focus, gain, boundary identification, or perform other auto-features. On the other hand, an EO sensor operated at high levels of autonomy could scan the environment, find and identify potential targets, and then track them as necessary. Other aircraft mission systems could have varying degrees of autonomy depending on the aircraft's design.
- **Teaming**. Humans and machines conducting MUM-T operations must share data about their own activities and receive the same information from teammates. At the low end of automation, an unmanned teammate that is performing as a missile carrier and launcher—a "missile truck"—would be able to station-keep in multi-aircraft formations as assigned by the formation's flight lead, then employ its weapons when directed. At the high end of autonomy, Teaming decisions are made by the machine, which ingests relevant data into decision-making algorithms and outputs a plan for the next task. Instead of simply performing as an on-demand missile truck, high Teaming autonomy might enable an ATA to act as a "smart wingmen" that autonomously flies dynamic formation tactics, manages its own sensors, shares relevant information, takes its own shots, and potentially even suggests or directs appropriate maneuvers to its flight lead.

The Warfighter View is intended to describe unmanned aircraft in terms of operational behaviors. The criteria and language derived from the Warfighter View will be the basis for conveying to engineers, senior leaders, policymakers, and industry how warfighters will use the platform to execute missions. Each set of stakeholders will use information from Warfighter View to make decisions in their respective areas, such as the need for new operational concepts, force employment policies, or program funding. Just think of the utility this would provide informing key leaders on Capitol Hill; instead of a confusing set of technical jargon, program officials could clearly articulate where they were directing development dollars, where risks were most pronounced, and how this related to mission performance. Of note, aerospace engineers can use the Warfighter View framework to decompose the macro-level operational behaviors desired by warfighters into the underlying auto-features, functions, technology, and data that will realize them.

> **Instead of a confusing set of technical jargon, program officials could clearly articulate where they were directing development dollars, where risks were most pronounced, and how this related to mission performance.**

Part 2 of the Autonomy Framework: The Engineer View

Combat aviation is an extremely complex endeavor that requires highly advanced specialized and generalized decision-making. This is one reason that the development of autonomous combat aircraft is so difficult, as well as why warfighters retain a skepticism about the ability of technologists to effectively replicate the behaviors and decision-making skills of human pilots. Developing a framework based on the cognitive tasks of combat pilots—Core, Mission, and Teaming—offers an opportunity to rationally decompose these skills for engineers developing future UAVs and increase warfighter trust. Warfighters must have confidence that ATAs will behave in ways that warfighters expect, are mission effective, and are safe. Teammate behavior should be appropriate and predictable but not overly rigid or brittle. It should be responsive to the ever-changing battlespace environment but should do no harm to U.S. and coalition forces through either commission or omission.

Developing a framework based on the cognitive tasks of combat pilots—Core, Mission, and Teaming—offers an opportunity to rationally decompose these skills for engineers developing future UAVs and increase warfighter trust.

In the Warfighter View, operators describe desired UAV system behaviors and the auto-features necessary to create those outcomes. Defining behaviors and the needed level of autonomy for the associated auto-features enables technologists and engineers to translate the Warfighter View into Engineer View information. Behaviors are categorically and hierarchically decomposed by technologists into auto-features and functions. Auto-features are developed from sets of functions. Functions are the specific hardware components and software modules that enable the execution of an auto-feature. Functions can be even further decomposed down to the most elemental pieces of specific parts, mathematical algorithms, and training data. Functions are an input to an auto-feature, but like an auto-feature can be combined in different ways to generate different auto-features.

Figure 8 illustrates a notional Engineer View. The Engineer View takes the desired level of autonomy for each autonomy category from the Warfighter View and uses it as a basis to guide the functional and physical decomposition of the system. In essence, the Engineer View provides a structured approach for the application of traditional systems engineering methods to the development of autonomy for unmanned aircraft. Key traditional systems engineering methods include functional analysis, physical analysis, and functional allocation.[21] Functional analysis decomposes a system into the functions and sub-functions required for it to fulfill its intended purpose. Similarly, physical analysis decomposes a system into the sub-systems and components necessary to provide the functions identified in functional analysis. Functional allocation is the process of assigning every identified function and sub-function to a sub-system or component, ensuring that every function is instantiated somewhere in either hardware or software and that every component is tied to at least one system function.

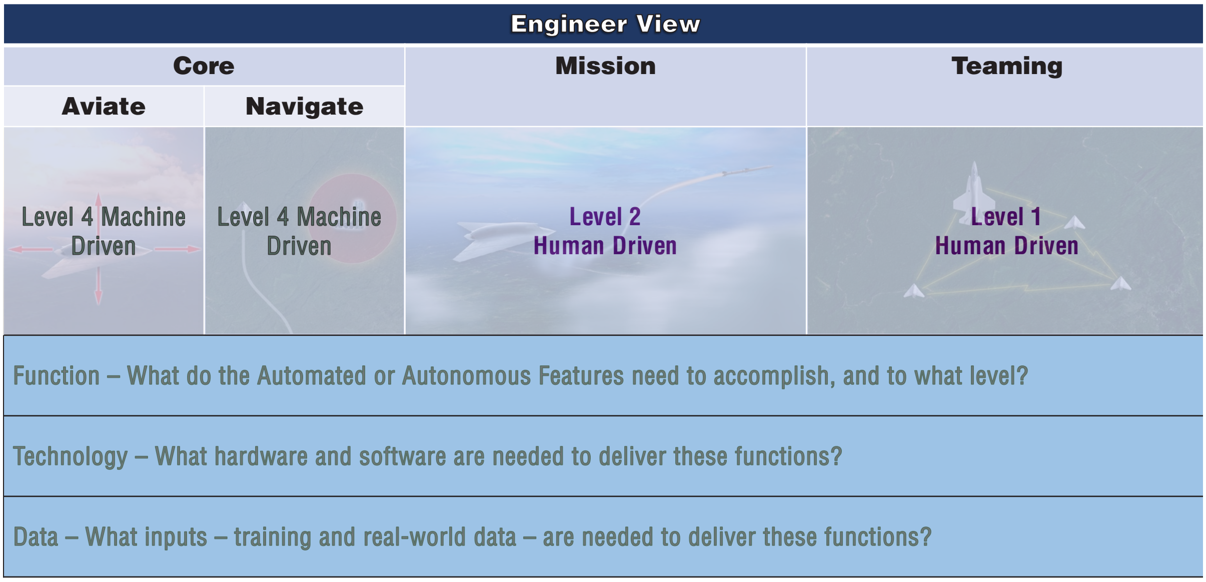

Figure 8. The engineer view takes the desired levels of autonomy for each autonomy category from the warfighter view and provides a structured way to decompose the autonomous capabilities into the necessary functions, technology, and data. In this example, the Warfighter View assigned autonomy level 4 to both Core Aviate and Navigate categories, while assigning level 2 to Mission and level 1 to Teaming.

Credit: Mitchell Institute, Heather Penney, Maj Christopher Olsen, Kamilla Gunzinger, and Zaur Eylanbekov

The Engineer View serves as a kind of "true north" as aerospace engineers embark on the development of an unmanned aircraft system, ensuring the collection of functions and technology they design will result in a platform that aligns with the warfighters' vision of how it will be used. The following illustrative examples of functions, technologies, and data relevant to the Core, Mission, and Teaming autonomy categories are intended to make these relationships less abstract.

- **Core Aviate** key functions and sub-functions include maintaining aircraft altitude, adjusting its pitch angle, executing coordinated turns, deflecting control surfaces, and adjusting engine power. The technologies necessary to implement these functions may include fly-by-wire flight controls and a digital flight computer. Core Aviate auto-features will require similar data to the information provided by a traditional human-readable flight instrument cluster such as aircraft altitude, airspeed, and bank angle, along with more detailed data such as the angle and rates for roll, pitch, and yaw.
- **Core Navigate** auto-features will be supported by functions such as flight path planning, waypoint following, and navigation relative to other aircraft. Relevant technologies might include cameras, radars, and path planning algorithms. To support navigation, the aircraft's systems will need to access data such as the aircraft's current location, altitude, airspeed, and groundspeed, as well as the location of any known obstacles or threats and the boundaries of permissible airspace and no-fly zones. Relative navigation will require data on the distances; closure rates; and vectors from the UAV's manned and unmanned teammates, other friendly forces, and threats.
- In the **Mission** category, relevant functions include sensor operation and determining aircraft positioning for optimal sensor performance, target identification, and task sequencing.[22] Technologies might include sensors, hardware, and software for processing sensor data, task optimization algorithms, or neural networks trained for automatic target recognition. Data needs for Mission may include aircraft orientation, distance to a target,

munitions remaining, and training data to "teach" a system's algorithms sequencing and decision-making.

- For **Teaming**, functional analysis will determine what information should be shared across different teammates or other entities to allocate and coordinate their tasks for an operation, such as cooperatively engaging a target. Technologies for sharing this information would be things like computers for onboard data fusion, algorithms that allocate tasks, and radios to transmit data. Data needs may include current location, the locations of teammates, both raw and processed sensor data, or a database of proven tactics and techniques.

In practice, the Engineer View's aim is to translate the desired operational capabilities from the Warfighter View into the actual hardware and software that will compose the fielded system. In turn, the Warfighter View captures the vision and intent for the system, relaying the intended use case, the key capabilities, and how much human decision-making and control will be required to use it. It should be noted that a portion of the data that feeds Core, Mission, and Teaming functions will need to be stored onboard an aircraft so that it can be downloaded post-mission to be processed, cleaned, and labeled to retrain machine learning algorithms or develop new ones that will become the backbone of an increasing number of auto-features going into the future. Determining what kind of data to capture and how to use it to improve battlespace awareness, operations, and autonomy will be crucial to achieving combat superiority.

The Framework in Action

How could warfighters and aerospace engineers use this framework to develop an autonomous teaming "missile truck" UAV? In this example, operators use the proposed framework's Warfighter View categories and autonomy levels to describe the behaviors of an autonomous teammate capable of launching weapons at targets. Technologists then decompose behaviors and auto-features described in the Warfighter's View to the Engineer View's outcomes of function, hardware and software, and even the data needed to train the algorithms. This dialogue is not intended to be one-way—when properly used, the framework should also facilitate broader decisions on technology readiness levels, auto-feature tradeoffs, how levels of autonomy could impact the development of operating concepts, and even UAV developmental and fielding timelines.

An operational example: The missile truck

A missile truck describes an unmanned teammate aircraft that carries additional weapons that can be used by a flight lead. Missile truck UAV wingmen can significantly increase the strike capacity of penetrating stealthy fighters and bombers that are constrained to carrying weapons internally to maintain their survivability. Air Force operators can use the framework's Warfighter View to develop operational concepts and communicate with greater granularity to policymakers, engineers, and other stakeholders on how they envision a missile truck should perform. This allows operators to right-size the levels of auto-features for the missile truck in each Warfighter View category to meet mission requirements instead of waiting for engineers to perfect systems with full autonomy. It could accelerate the development of an autonomous aircraft as well as increase its trustworthiness because warfighters will better understand its behavior, capabilities, and limitations. Hopefully, this will spur warfighters to figure out even more new ways to employ autonomous aircraft.

Figure 9. Depiction of a notional ATA missile truck.

Credit: Zaur Eylanbekov

Applying the Two-View Framework on a Notional Missile Truck			
	Warfighter View		Engineer View
Core Aviate	Must be able to handle all phases of flight from takeoff to landing without any need for direct control from a remote pilot or the flight lead.	Autonomy Level: Level 3 Full Automation to Level 5 Autonomous (desired)	Full autonomy may be beyond the capabilities of current technologies, and thus increase time and cost of development. Pursuing Level 3 could help speed a minimum viable capability to the field while work on incremental software or hardware upgrades to increase autonomy continues.
Core Navigate	At a minimum, must be able to maintain designated formation positions without hitting the ground, its flight lead, or other aircraft. At more advanced levels, might be able to fly dynamic tactics and conduct threat avoidance and defeat maneuvers	Autonomy Level: Level 3 Full Automation to Level 5 Autonomous	Level 4 Semi-autonomous may be faster to develop and train than a Level 3 system. Engineers can discuss the tradeoffs in development and fielding of pursuing higher or lower levels of autonomy.
Mission	The human flight lead selects which ordinance to use, when, and on which target. Additional autonomy may provide extra options that increase lethality and mission effectiveness.	Autonomy Level: Level 1 Low Automation to Level 3 Full Automation at a minimum	The benefit to the warfighter of a higher level of automation may be initially outsized by increased cost and impact on a ATA's development. Conversely, higher levels of mission autonomy may eventually provide even more benefit, to the point where the missile truck truly becomes a smart teammate. This depends on increasing warfighter trust in autonomy.
Teaming	Partial automation is sufficient to merely exchange data directly to a flight lead, assuming little need for onboard data processing or data fusion.	Autonomy Level: Level 2 Partial Automation at a minimum	Teaming at higher levels of autonomy would increase focus on processing and machine decision-making capabilities, which would also increase the need for real-time data. Increasing warfighter trust in autonomy will be key to maturing teaming capabilities and operations.

Figure 10. An example of how the proposed framework could be applied to a notional ATA missile truck Credit: Mitchell Institute, Heather Penney, Maj Christopher Olsen, and Kamilla Gunzinger

Operational concepts for a missile truck teammate might have the UAV wingman take off autonomously as an integral part of the flight and then immediately take position in a designated formation. Alternately, a missile truck might already be airborne or have launched from a different location and is maintaining a holding pattern until joining up with its assigned flight lead. From the flight lead pilot's perspective, the missile truck teammate should be a reliable wingman capable of flying in a required formation—at the very least, the flight lead should not have to worry about the UAV's position.[23] A flight lead should be able to command the use of a UAV teammate's weapons against targets without having to complete a complex chain of actions. More advanced teammates may have the ability to fly detached formations of mutual support, enhance flight lead situational awareness with cooperative sensing, and even prosecute attacks against high-risk threats to protect their manned flight leads. When it is time for the formation to return to base, the UAV teammate should follow the manned flight lead and autonomously loiter some distance from the airfield until it is cleared for an autonomous landing. Alternately, if a UAV teammate has enough remaining fuel or weapons, it might enter a holding pattern awaiting a new flight lead and departing once it either reaches bingo fuel or no longer has any weapons.[24]

Missile truck Core Aviate. With the above mission scenario in mind, what might the Warfighter View look like for the hypothetical missile truck? For Core Aviate, the teammate must be able to handle all phases of flight from takeoff to landing without any need for direct control from a remote pilot. Possible ranges of autonomy for Core Aviate could include level 3 Full Automation to level 5 Autonomous. Robust, rules-based automation might be sufficient to conduct the basic flight and engine controls across the range of operational concepts, as well as maximize the performance of the aircraft without exceeding critical flight or engine parameters. Depending on the desired level of contingency and emergency management, however, warfighters may want more autonomy available in levels 4 and 5.

The two-part proposed framework may help operators make tradeoffs or decisions regarding requirements versus "desirements." Level 5 autonomy, for example, might be beyond the capabilities of current technologies. Thus, making it a requirement would increase the time and cost of developing a UAV system. Moreover, warfighters working with technologists may uncover limitations and constraints of level 3 automation that would prevent the UAV teammate from fully executing more advanced tactics and concepts. Initially accepting a lower level of automation could help speed a minimum viable capability to the field while engineers continue to work on incremental software or hardware upgrades that would increase the UAV's autonomy levels.

The two-part proposed framework may help operators make tradeoffs or decisions regarding requirements versus "desirements."

Missile truck Core Navigate. Depending on how advanced and dynamic the operational concept for the missile truck, level 3, Full Automation, to level 5, Autonomous, would be required for Core Navigate. At a minimum, the aircraft must be able to maintain designated formation positions without hitting the ground, its flight lead, or other aircraft. At more advanced levels, the UAV teammate might be able to fly dynamic tactics and conduct threat avoidance and defeat maneuvers. A "dumb wingman" that station-keeps and maintains a position to fire weapons likely does not need more than level 3 for Navigation, whether absolute or relative. More advanced operational concepts would require either greater direction and workload on the flight lead or require higher levels of autonomy.

Similar to Core Aviate, warfighters working together with engineers can have more productive conversations about where the optimal spot is for the right level of autonomy and required auto-features. Because levels 1 through 3 are largely deterministic, it may be that level 4 Semi-autonomous, in this case, may be faster to develop and train than a level 3 system. A paradox of machine learning is that rules-based programming is not always faster or easier. Regardless, the behaviors and auto-features of the Warfighter View will allow operators to better communicate the outcomes and actions they want and have more productive dialogue with technologists.

Missile truck Mission. Different systems in the Mission category can range dramatically across the autonomy spectrum. At its most basic level, the missile truck is essentially a "dumb" flying magazine with little Mission awareness. The human in the lead aircraft is responsible for selecting which ordinance to use, when, and on which target. This overall Mission level 1 autonomy missile truck would receive its targeting data and firing commands from the lead aircraft, providing extra missile capacity but little else. From an Engineering View, this level of functionality would primarily require data provided over a communications link to receive launch commands from the flight lead. Level 1 would not have the ability to command Core to maneuver the UAV to optimize its weapon launch envelope. Levels 2 to 3 of autonomy may provide extra auto-features and additional formation flying tactics, contractual targeting, and other pre-defined tactical options that increase the UAV's kinematic lethality and mission effectiveness. The benefit to the warfighter of a higher level of automation may be greater than expected if these functionalities can be delivered without minimal increased cost and impact on a UAV's development.

Warfighter trust in the machine's decision-making and behavior will be crucial to fielding higher levels of autonomy. If auto-features are appropriately representative of human cognitive decision-making, operators may be more accepting of less deterministic levels of autonomy.

Higher levels of Mission autonomy may provide even more benefit, to the point where the missile truck truly becomes a smart teammate. At autonomy levels 4 to 5, the UAV teammate may fly unscripted or detached formations and even execute independent operations in high-stress scenarios. These levels of Mission autonomy will likely require additional sensors; more data; and more complex algorithms, training repetitions, and training data. Warfighters may be skeptical regarding the trustworthiness of non-deterministic autonomy and instead prefer a more complex level 3 Full Automation UAV, even though rules-based automation may be thornier and more time-consuming to develop. When it comes to Mission, warfighter trust in the machine's decision-making and behavior will be crucial to fielding higher levels of autonomy. If auto-features are appropriately representative of human cognitive decision-making, operators may be more accepting of less deterministic levels of autonomy.

Missile truck Teaming. Like Mission, the Teaming needs of a missile truck are dependent on the complexity of the operational concept it is supporting. Level 2 Partial Automation is probably sufficient if all the teammate needs to do is exchange data directly with its flight lead with little onboard data processing or data fusion. At this level, decisions about how the missile truck will fly designated positions in a formation with other aircraft and collaborate with manned combat aircraft as directed. From the Engineering View, Core Navigation auto-features will interact with Teaming to maintain designated formation position by using GPS or INS position, closure, and trajectory information of the flight lead and the missile truck. Mission data, such as any sensor information, weapon status, and launch criteria, will be shared with the flight lead or other entities—Teaming is what manages this data.

As the complexity and dynamism of an operational concept increase, so must the unmanned teammate's autonomy to avoid task saturating the lead pilot. From the engineer's perspective, this will require more real-time automatic data exchange between the flight lead and unmanned teammate so the teammate can begin to anticipate the needs of the flight lead and associated tactics. Mission synchronization with the flight lead and other battlespace entities may even result in the teammate suggesting tactics or actions to the flight lead. Like Mission, Teaming is more than simply flying a good formation. Teaming at higher levels of autonomy will have an increased focus on processing and machine decision-making capabilities. This will also increase the need for real-time data.

Again, like Mission, human trust in the ATA's auto-features and associated behavior*s* will be key to maturing Teaming capabilities and operations. This will require warfighters and engineers to engage in dialogue early on in the conceptual and design process to identify the right levels of autonomy for new UAVs and how their auto-features can deliver the desired vehicle behaviors in the battlespace. Because functions in the Core, Mission, and Teaming categories interact to deliver a particular behavior, and auto-features are often used for more than one behavior, warfighters and engineers must work together to better understand these interactions and interdependencies. This framework can also help to manage developmental risk because the exchanges between warfighters and engineers can identify when an 80 percent solution is sufficient to meet the warfighter's need and still support the other required behaviors.

Acquisition example: Accelerating delivery of autonomous UAVs to warfighters

The proposed Two-View Autonomy Framework for Unmanned Aircraft also has the potential to accelerate the development and delivery of autonomous teammates to the field. Because the framework facilitates a shared understanding between warfighters and engineers regarding the autonomous functionality of a UAV teammate, the framework can serve to right-size autonomy in these aircraft. Right-sizing is crucial to identifying where the *real value is provided to the operator* and determining the time needed to develop a particular autonomous UAV. Using the framework to identify the appropriate level of autonomy a category needs to deliver a specific auto-feature or behavior allows engineers to accelerate the delivery of a minimum viable product. Without the framework, well-intentioned requirements officers may write either overly ambitious or insufficient autonomy requirements that will increase the time and cost of a UAV program. In this case, right-sizing also means identifying more appropriate category levels and constraining warfighter appetites as necessary.

Right-sizing is crucial to identifying where real value is provided to the operator and determining the time needed to develop a particular autonomous UAV.

The two-view framework can help senior leaders and their staffs to make tradeoffs between cost, schedule, and risk when determining UAV program requirements. It will also help explain the rationale behind these decisions to oversight bodies on Capitol Hill and beyond. DOD's Request for Information (RFI) process demonstrates how the two-view framework can facilitate these tradeoff decisions. During the RFI stage of a program, the U.S. Government canvases industry to determine what technologies they have on hand or in development that may be able to fill a particular materiel need. The RFI process is not a contract solicitation but simply a mechanism for the government to understand the state of the industry and the maturity of technical solutions for a particular problem. In the case of current and emerging autonomy technologies for unmanned aircraft, the framework delivers a common and consistent language to facilitate feedback and support tradeoff analysis between the government and industry.

The two-view framework can help senior leaders and their staffs to make tradeoffs between cost, schedule, and risk when determining UAV program requirements.

For instance, suppose CONOPS development suggests a UAV needs a level 4 Mission capability, but industry feedback through the RFI process indicates the technologies required to attain level 4 autonomy are at a low Technology Readiness Level (TRL) and will require additional investment and time to mature. If this does not cause CONOPS to revise their requirements' timeline and budget, they will have to decide if they are willing to accept higher operational risk. Because the framework does not treat autonomous aircraft as monoliths and breaks their autonomy down into categories defined by behaviors and auto-features, it can help decision-makers identify specific areas where a system's cost would be prohibitive, maturing the technology would take too long, or the risk of entrusting a machine with so much autonomy is too high. Alternately, industry may respond to an RFI by suggesting a higher level of autonomy would require less time to develop and field compared to a lower level of automation.

Just as the framework provides a structure for industry to communicate the hardware, software, and data it would need to deliver certain auto-features and how those would impact other vehicle behaviors, it can also help operators focus on needed behaviors and supporting auto-features. Without the ability to break teammate behaviors down into categories, warfighters may be tempted to think of autonomous systems as all-or-nothing proposals. In practice, the ability to right-size the levels of autonomy in each of the framework's categories can accelerate the delivery of a system and ensure that its autonomy is appropriate for a required operational capability.

The framework provides military leaders with a factual basis—not conjecture or pixie dust—for making tradeoffs or trade-ups that balance the capability needs of warfighters with technological and fiscal constraints.

Bottom line, DOD can use all of this information to decide if the additional investment needed to mature technologies to achieve specific levels of autonomy is worth it, or if a lower level of autonomy, that can be realized in the near term with off-the-shelf solutions, will suffice. The framework provides military leaders with a factual basis—not conjecture or pixie dust—for making tradeoffs or trade-ups that balance the capability needs of warfighters with technological and fiscal constraints. The demands of the current security environment, monetary pressures, and the need for rapid solutions require this enhanced level of precise conceptual formulation. It is hard to arrive at a desired destination without effective communication and a set of intelligible directions over understood terrain.

Recommendations and Conclusion

Teaming increasingly autonomous UAVs with manned aircraft will be critical to developing future air forces that have the resilience, capacity, and lethality needed to compete and win in a peer conflict. Developing these UAVs—and the autonomy that will drive them—is an urgent priority for the Air Force. Other nations, notably China, are making strides in these technologies and may even have already surpassed the United States. Yet defense strategists, policymakers, and warfighters lack an in-depth understanding of autonomy, artificial intelligence, and their current technology readiness levels. This lack of understanding can breed misapplication, mistrust, and resistance to these crucial technologies, causing a strategic setback measured in program delays and budget overruns that risk a U.S. defeat against determined adversaries. A framework is required to help the U.S. defense community better understand the different autonomous functions and then define and develop systems with the appropriate levels of autonomy needed for MUM-T operations.

The Two-View Autonomy Framework for Unmanned Aircraft establishes a common language and consistent structure for prioritizing research and development efforts, establishing system requirements, and developing MUM-T operational concepts. Normal coordination efforts during these activities, such as exchanging slide decks or the occasional site visit, will not suffice to maximize the potential of this framework to accelerate the development of next-generation UAVs. To gain the fullest benefits of the framework, early, close, and continuing collaboration between warfighters and engineers will be necessary throughout the entire lifecycle of these important systems.

At its heart, the framework is about demystifying autonomy in operational terms and establishing a shared understanding and language that translates across other stakeholder communities. To gain wide acceptance and find practical application in the day-to-day processes that govern unmanned aircraft requirements, design, and development, this autonomy framework requires an owning organization—optimally AF/A5—to champion it across the Air Force enterprise, with relevant policymakers in DOD, Congress, and across industry. As such, ownership of the framework should reside with an operationally focused organization that can act as a steward of its application, revision, and updates as needed to remain applicable to the demands of modern warfare. To this end, this report makes the following recommendations:

- **The Air Force needs an Autonomy Framework to guide its next-generation UAV requirements definition, acquisition programs, and CONOPS and TTP development.** Air Force warfighters, aerospace engineers, and acquisition professionals currently lack a framework that helps them understand what autonomy is and how it can be applied to future MUM-T operational concepts and aircraft.
- **The Two-View Autonomy Framework for Unmanned Aircraft offers a model that the Air Force can use to facilitate greater collaboration between warfighters, technologists, and aerospace engineers.** Based on the mental tasks and functions of combat pilots, this framework can help warfighters understand autonomous systems in operational terms they are familiar with. The framework then provides these operational perspectives to technologists and aerospace engineers to guide their systems development efforts. While this framework is a model that can facilitate the

communication and collaboration needed to accelerate the development and fielding of MUM-T UAVs, it is not intended to constrain either warfighters or engineers.

- **The Air Force Deputy Chief of Staff for Strategy, Integration, and Requirements (AF/A5) should have formal ownership of the framework, in close collaboration with the Deputy Chief of Staff for Operations (AF/A3), Air Combat Command, and Global Strike Command.** With a mix of combat-experienced operators and significant planning infrastructure, AF/A5 has both the charter and operational expertise to apply the autonomy framework effectively across the range of necessary stakeholders. On the Air Staff, the AF/A3 has deep ties into the operational community, the Air Force Warfare Center, and the warfighting major commands. Together, the AF/A5 and AF/A3 can champion and implement the Two-View Autonomy Framework for Unmanned Aircraft in the service's requirements definition and the acquisition and development processes.
- **Stakeholders across the enterprise should embrace and broadly use this two-view framework to guide autonomy research, development, and experimentation, as well as to inform the development of new tactics, techniques, procedures, and operational concepts.** Using the framework to its fullest potential will require the A5's staff, operators, acquisition professionals, technologists, and industry to maintain a tight and collaborative interaction throughout the requirements definition, acquisition, and development lifecycle. The utility of this framework goes well beyond the traditional acquisition process. By employing this framework across the lifecycle of MUM-T UAVs, this framework can encourage warfighters and technologists to be more creative as they develop innovative autonomous teaming aircraft CONOPS, TTPs, post-fielding experiments, and continuing modernization upgrades.

Autonomy for unmanned aircraft is a challenging set of problems. Operational concepts need to be developed to take advantage of this emerging technology, and the research and development efforts to support it need to be guided accordingly. The Two-View Autonomy Framework for Unmanned Aircraft breaks down those problems and offers a solid foundation to build a cohesive approach to autonomy and manned-unmanned teaming. As a unifying thread across the vision documents, strategies, flight plans, operational concepts, research and development efforts, and programs that compose the Air Force's push toward operationalizing autonomy for unmanned aircraft, this framework establishes a common language and structure across stakeholders. A shared understanding can increase consistency within and between operational concepts and form a rational and reliable basis for prioritizing research and development. It is imperative to have a framework in place that enables the Air Force to harness the power of autonomy to maintain its long-held airpower advantage.✪

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16 Ibid.

17 Performance-based operations Aviation Rulemaking Committee/ Comercial Aviation Safety Team Flight Deck Automation Working Group, Operational Use of Flight Path Management Systems (Washington, DC: FAA, September 5, 2013).

18 The Mission category contains the necessary behaviors, auto-features, and functions to successfully execute doctrinal Air Force missions. To achieve these doctrinal missions, the well-established tactics, techniques, and procedures (TTPs), gleaned from decades of hard-earned combat experience, are encoded into the functionality contained within the Mission category. "U.S. Air Force Doctrine," U.S. Air Force.

19 The framework does not include level 0, or no automation. Although level 0 might be considered a natural baseline as a wholly manual level, virtually all military aircraft have some level of automation, and thus including a level 0 would add little to the framework.

20 This means level 3 systems are compatible with the traditional verification and validation (V&V) paradigm of developmental test and

evaluation. With traditional V&V, a system is stimulated with all possible or plausible combinations of input to ensure it responds as intended (verification, or did we build the thing right) and that the response achieves the desired effect (validation, or did we build the right thing). Traditional V&V breaks down for levels 4 and 5 systems because the systems are non-deterministic.

21 Dennis M. Buede, The Engineering Design of Systems: Models and Methods, 2nd Edition (Hoboken, NJ: John Wiley & Sons, Inc., May 2008).

22 The decision of where to position for optimal collection is a Mission function, but executing the aviation and navigation tasks to get into position are a Core responsibility; this speaks to the interactions between categories discussed previously.

23 More advanced UAV teammates might be able to execute dynamic tactics, electronic attack, or provide additional sensing to the flight lead.

24 Bingo Fuel is the minimum amount of fuel needed to safely reach the closest airfield or backup landing area.

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