



Five Imperatives for Developing Collaborative Combat Aircraft for Teaming Operations



By Heather R. Penney

FIVE IMPERATIVES FOR DEVELOPING COLLABORATIVE COMBAT AIRCRAFT FOR TEAMING OPERATIONS

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Key Points

The capability and capacity of the U.S. Air Force's current force design fall short of requirements to deter and prevail against Chinese aggression.

Chinese forces plan on conducting large-scale systems warfare in the Indo-Pacific. The U.S. Air Force must develop innovative operating concepts and grow its force size, resiliency, and ability to present complex challenges to counter this threat.

A family of unmanned collaborative combat aircraft CCA fielded at scale would help realize this, create a more attrition-tolerant/resilient force mix, and provide theater commanders with a strategic reserve for surge operations.

Understanding human-machine teaming dynamics is foundational to the development of CCA algorithms and software "brains" that drive CCA behaviors.

Involving operators early in the development of CCA teaming dynamics and incorporating warfighter-informed programming into CCA design will be crucial to their operational effectiveness.

The Air Force should improve its understanding of five human-machine teaming dynamics to guide its CCA development: building combat-effective human-CCA teams; increasing warfighter understanding and trust in CCA technologies; enhancing the dependability of CCA; devising mechanisms to control teaming operations in contested environments; and managing aircrew workloads created by teaming operations.

The Air Force must also fully integrate its warfighters in efforts to better define and understand each of these dynamics.

Abstract

The Air Force lacks the force capacity, lethality, and survivability needed to fight a peer-level conflict with China. To address these shortfalls, Air Force leaders are making significant decisions about the service's future force structure based on the promise of collaborative combat aircraft (CCA) technologies. A family of CCA fielded at scale could increase the Air Force's combat capacity, create a more attrition-tolerant/resilient force mix, provide theater commanders with a strategic reserve for surge operations, and enable complex operations that complicate an adversary's defenses.

While this approach has great potential, current CCA development efforts primarily focus on mission tasks. This is problematic because the effectiveness of CCA in combat will be primarily driven by how well they team with humans, not just capabilities such as weapons and sensors. From the start, highly experienced warfighters must be integrated with skilled technologists to structure teaming dynamics, using human flying formations as models. Because teaming dynamics will interact with all other CCA autonomy software, teaming must be built in from the very beginning. To achieve the full potential of human-CCA teams, the Air Force should consider the following five imperatives for CCA development:

1. Optimize the composition of human-CCA teams based on each teammate's strengths.
2. Include operators in CCA development and provide them with the tools they will need to understand how CCA should perform in the battlespace.
3. Ensure warfighters can trust and depend on CCA autonomy.
4. Ensure warfighters can maintain assured control over CCA in highly dynamic operations.
5. Ensure teaming workloads are manageable for humans.

Introduction

Collaborative combat aircraft (CCA) technologies and concepts for teaming CCA with crewed aircraft promise to provide the U.S. Air Force with new, potentially decisive combat advantages in future peer conflicts. For the purposes of this assessment, CCA are semi-autonomous uncrewed combat aircraft that are equipped with a mix of sensors, weapons, and other equipment that can be tailored to perform different missions.¹ This means that CCA autonomy will need to be a mix of traditional, deterministic software and machine learning algorithms and will still require human interaction for the aircraft to execute their mission. A family of CCA fielded at scale would increase the Air Force's combat capacity, create a more attrition-tolerant/resilient force mix, provide theater commanders with a strategic reserve for surge operations, and enable complex operations that complicate an adversary's defensive challenge. Prevailing in peer conflicts in highly contested operational environments will require air forces that have all these attributes—and CCA promise to provide an affordable means for the U.S. Air Force to create this force design.

However, Air Force leaders are making significant and possibly irreversible decisions about the service's future force structure based on the promise of CCA technologies. One key objective is to move away from reliance on a small number of major weapon system types toward a future force that is more disaggregated and has the increased capacity, resiliency, and survivability to defeat peer adversaries. The Next Generation Air Dominance (NGAD) family of systems may be the premier Air Force program of record for pioneering this new, collaborative combat aircraft concept.² Although details about the NGAD program are classified, it is likely that its system of systems will depend upon CCA and other off-board capabilities to achieve decisive mission effects in highly contested environments.

While this force design approach has great potential, CCA teaming concepts of employment have not been developed, and the technologies—including artificial intelligence—they depend upon have not been definitively proven and are not ready for fielding. Yet the Air Force is shrinking its current combat forces by retiring weapons systems with no replacements on hand and even slowing procurement of new aircraft to achieve this future force vision.³ Moreover, developing an understanding of *how* CCA will team

The Air Force Must Get CCA Development Right

The Air Force is making a big bet that CCA will be effective in future operations. Developing, producing, and fielding CCA will not be cheap and will require the Air Force to make budget tradeoffs that affect its other forces and capabilities. During an FY 2023 budget briefing, Secretary of the Air Force Frank Kendall spoke to the “hard choices” he made to divest current aircraft “in order to have the resources to modernize.” Given these tradeoffs, the Air Force must develop a family of CCA with the right capability attributes. Most importantly, these CCA must be able to team effectively with humans in highly dynamic operations. The stakes are incredibly high, and the risks are significant given the Air Force's level of divestitures and the fact that CCA technologies are—so far—unproven in combat.

An Example of Human Factors Engineering: F-4 Fighters

F-4 fighters are an example of how aircraft designers in the 1960s began to recognize the need to incorporate human factors in complex military aircraft. The F-4 was a highly advanced and extremely complex fighter for its time. Designed with one of the most powerful radars available, McDonnell Aircraft engineers were so concerned that the pilot would become overloaded by the simultaneous tasks of maneuvering the aircraft, managing the sensors, interpreting the instruments and scope, and flipping the switches to fire the AIM-7 Sparrow radar missile that they built in a second cockpit for the sole purpose of managing the sensors and weapons systems. Their concerns were not unfounded. System complexity and the volume of information coming to pilots were growing substantially and threatened to overwhelm pilots and degrade their mission effectiveness—and even basic flight safety. Adding a second pilot was McDonnell's answer. When the Air Force replaced the F-4 with the F-15 Eagle, it wanted a single-pilot fighter. Advances in human factors engineering and processing allowed the Air Force to develop this design and *increase the* information immediately available to pilots without maxing out their task burden.

with humans is largely missing from the Air Force's current efforts. To date, the service's research and development efforts have primarily focused on the most obvious problem of how to remove humans from CCA logic and control systems.

Without question, the Air Force's research labs and industry teams are making progress on important, foundational challenges related to CCA development, like autonomous flight control dynamics, flight safety, battlespace awareness, tactical decision-making, and sensing and maneuvering. What is lagging, or even absent, is warfighter involvement in the process of determining how CCA should interact with humans and what information humans need for those interactions to be effective in real-world operations. Failure to develop CCA teaming concepts of employment and an understanding of related teaming functions will undermine their potential to transform the Air Force's future battlespace operations. Warfighters should be—must be—involved in the early stages of the Air Force's CCA development programs to shape how these autonomous aircraft will operate alongside humans in the battlespace. Failing to do so risks developing suboptimal CCA designs that have reduced effectiveness in the battlespace.

This approach is not new—the need to understand and account for how humans interact with machines and vice versa has been a hard-won lesson learned by aircraft designers and engineers since the beginning of aviation. This is now called “human factors engineering,” which is a human-centered approach to the science of designing how humans interact with machines to enhance the performance of human-machine teams. Early cockpit designs did not account for the limitations of human perception, task loading, habits, cognition, and other behavior. Aircraft instrumentation and controls were often optimized for available space and weight in the confined spaces of a cockpit, not pilot performance. This contributed to aircraft incidents and accidents.

As aircraft became more complex, human factors engineering became a critical part of designing aircraft. Today's fifth-generation aircraft, like the F-35 stealth fighter, demonstrate how human factors engineering

and advanced processing technologies can streamline task loads and enable pilots to do what humans do best: perform high-order cognitive tasks like decision-making and battle management. Yet as the Air Force is embarking on developing CCA, they are neglecting their own important lessons learned regarding human factors. Collaborative combat aircraft are meant to team with a human warfighter, yet, for the most part, warfighters are being left out of CCA development.

The Air Force must deliberately prioritize human factor engineering as a first principle for developing CCA. The reasons for this are simple—human teaming concepts of employment and tactics are not something that can be figured out and bolted on after these systems are fielded. How CCA will collaboratively interact and operate with humans must be weighted, trained, and built into their hardware and algorithm designs from the beginning: they cannot be an afterthought. While CCA behaviors and algorithms will undoubtedly evolve over time, warfighters must be involved in their creation and iterative development.

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The absence of a human teaming focus and the omission of operator inputs to CCA development programs is already shaping and solidifying warfighters' skepticism of CCA potential. Warfighters may enthusiastically embrace the *concept* of and *requirement* for CCA to ensure mission success, but it is another thing entirely for them to accept that these promised technologies are real and will perform as advertised. Envisioning successful CCA combat operations against a peer adversary in a dynamic battlespace is a vastly different proposition from imagining how self-driving cars might perform on U.S. highways. Demonstrations of autonomous aircraft executing

complicated behaviors are increasing trust that autonomous technologies are moving in the right direction, but demonstrations are not enough. This doubt was captured by one Air Force operator who stated: "Sure, we've seen some great tech demos, but as a real capability that I could go to war with, they're not much farther along than PowerPoint."⁴

Government and industry aircraft design engineers have also reported that they view "warfighter lack of trust" as a major barrier to fielding CCA, much less achieving the full potential of CCA as autonomous teammates. A president of one leading autonomous technologies development company bluntly stated, "They just don't trust the systems. Anything we do to develop these capabilities is just a science project if operators don't trust them because then they'll never use them."⁵ There is more at stake with this issue than simply providing warfighters with warm fuzzies on the potential of CCA; failing to prioritize human teaming in CCA development increases the risk that they will not perform as needed in the battlespace.

The Air Force cannot defer developing a mature understanding of basic and essential collaborative aircraft teaming behaviors until after CCA teammates are fielded because human interaction dynamics must be part of their software programs, algorithm development, and training repetitions. If this does not happen, engineers may develop CCA that do not function effectively with humans and reduce the potential for

their teaming operations to succeed in high-end conflicts. These consequences are unacceptable, given the magnitude of strategic challenges Air Force leaders now face and the faith and resources they are committing to developing multiple CCA variants. In short, involving operators early on in developing an understanding of CCA teaming dynamics is crucial to their operational effectiveness. This study identified the following five broad teaming imperatives that the Air Force must prioritize as it develops CCA that will meet the needs of warfighters in complex and demanding battlespaces:

- 1. Create teaming concepts that will maximize the strengths of both CCA and piloted aircraft.** The effectiveness of CCA in combat will be primarily driven by *how well they team with humans*, not capabilities such as the weapons and sensors they carry. The Air Force has yet to develop and articulate operational concepts that will help describe the advantages that autonomous CCA teammates may provide in the battlespace. As a result, it is unclear how CCA will operate, maneuver, and otherwise partner with humans to exploit the strengths of both humans and machines. To harness the full potential of CCA, the Air Force must develop teaming operational concepts; teaming concepts of employment; and tactics, techniques, and procedures for how warfighters will work with CCA to exploit their unique attributes. Humans will then need robust, real-world training to master these tactics and develop confidence that CCA will provide them the combat edge they need in highly contested battlespaces.
- 2. Include operators in CCA development to ensure they understand how they will perform in the battlespace.** Autonomy and machine learning programs remain notoriously opaque to warfighters. Without an understanding of how CCA think, how they make decisions, and why they take certain actions, warfighters will be unable to anticipate how their autonomous teammates will react when given inputs and data. Involving warfighters in CCA development would improve their understanding of how CCA perceive, think, decide, and behave as they do. It would also improve their ability to exploit the unique attributes of their teammates while mitigating their vulnerabilities in complex and contested battlespaces.
- 3. Warfighters must be able to depend on CCA autonomy.** It will be difficult for warfighters to assess the dependability of their autonomous teammates if they lack the means to evaluate the real-time performance and accuracy of their CCA. This concern goes beyond the traditional DOD operational software tests for verification and validation or concerns regarding “hackability.” Humans will need confidence that their teammates will consistently maneuver safely and effectively, have an accurate and mutual understanding of the battlespace, share critical information, maintain the same tactical priorities, defer to their human’s control, and behave in ways that their humans expect and need.
- 4. Warfighters must have assured control over CCA in highly dynamic operations.** Human operators must have resilient and reliable means of controlling their CCA teammates in spectrum-contested environments where adversaries are attacking information networks to deny or collapse command and control across the force. CCA must continue to operate effectively to achieve their missions without communications in worst-case contingencies where datalinks are denied or break down. Moreover, humans must be able to dynamically adjust their level of control over their autonomous teammates based on real-time battlespace demands—especially when human task loads are high, and the situation may be surprising, unexpected, or confusing.

- 5. Human workloads must be manageable.** Humans must be able to communicate, collaborate, and control their CCA teammates with the least amount of friction inside their own cockpits, even as their own task-loading increases in complex battlespaces. Warfighters will not find CCA useful if managing their CCA teammates detracts from the performance of their primary mission duties to the extent that it jeopardizes mission success. These concerns extend beyond flight control mechanics to include communication, coordination, and other mission integration tasks.

As vital as autonomous teammates are to the Air Force’s future force design, CCA technologies are not yet mature or fully embraced by the operational community. Defense industry and Air Force research labs have so far primarily focused on decomposing mission tasks in solving the many complex technical problems associated with developing autonomous CCA. While they have made incredible progress, efforts to date have neglected developing an understanding of how CCA should team with piloted aircraft to achieve operational success. The Air Force cannot take a “build it, and they will come” approach to resolving this challenge. Warfighters will not develop trust and confidence in CCA if the Air Force fails to create concepts of employment for teaming operations and the software and algorithms necessary for humans to effectively command, control, and collaborate with their CCA teammates. It could also delay CCA programs to the point where the Air Force falls behind strategic competitors who seek similar capabilities.

Understanding, mapping, and decomposing how humans interact and integrate with each other in piloted formations can offer early and crucial insights into how teaming dynamics may be structured between humans and their autonomous teammates.

The solution is to involve warfighters in CCA development so they will perform specific teaming functions and tasks in ways that are trustworthy and effective. The foundational teaming behaviors that will make CCA successful will also interact with their other mission tasks and cannot be bolted on after fielding. How formations of human-piloted aircraft operate together may offer an initial model for doing this.⁶ Understanding, mapping, and decomposing how humans *interact and integrate with each other* in piloted formations can offer early and crucial insights into how *teaming dynamics* may be structured between humans and their autonomous teammates, even as those collaborations and formations evolve.

Background: Dull, Dirty, and Dangerous

Uncrewed aircraft used by the Air Force since WWII generally fall into two categories: those that fly predictable and unchangeable pre-programmed flight paths controlled by an autopilot or those that are remotely piloted by humans through line-of-sight datalinks. These uncrewed aircraft were used to conduct niche missions that are not ideal for humans or missions that are considered dull, of long duration, dangerous, or dirty. However, there are tradeoffs and limitations commanders must consider when using these basic “drone” capabilities, including their limited ability to respond in real-time to mission changes or unforeseen events in their operating environment. Before satellite communications, limitations in line-of-sight datalinks needed to remotely control drones over long ranges into high-risk environments required controllers to pre-program them to perform their missions and use a set menu of responses in the event of component failures or other contingencies while in flight. Moreover, early drones lacked the capability to team with crewed or other uncrewed aircraft. It was not until the Predator series of aircraft was fielded that remote human operators could collaborate with piloted aircraft. While these operations still have limitations, they represent a major step toward developing true collaborative combat aircraft.

An Example of Early Pre-programmed Aircraft: The “Kettering Bug”

The earliest successful uncrewed military aircraft saw its first flight less than 20 years after the Wright brothers took to the air. In 1918, the Army Air Services tasked electrical engineer Charles Kettering—founder of the Delco electrical components company—with building a pilotless flying machine capable of hitting a target at ranges beyond the reach of artillery. With the help of Orville Wright, Kettering designed a small, automated biplane that they thought would perform as a “self-flying aerial torpedo.” Nicknamed after its designer and appearance, the Kettering Bug was more cruise missile than drone.

Dull, Dirty, or Dangerous...

DOD describes “dull” or dumb missions as fixed, repetitive, or under-stimulating tasks that can be performed by automated systems to free human operators for other, more dynamic missions. There are also clear advantages to using automated systems when feasible for very long-duration missions that could stress or even exceed human physiological tolerances and lead to human errors due to exhaustion. “Dirty” missions may expose aircraft and their human crews to threats such as unsafe chemical or radiological contaminants, and “dangerous” missions are flown into environments that are so high threat that the loss of human life is too great to chance. In these cases, uncrewed aircraft may be the better, lower-risk choice to achieve mission success.

The Bug was also small, simple, cheap to build, and conceived of from the outset as a weapon, not a replacement for the manned aircraft of the day. A gyroscope and barometer were the only avionics onboard. The rest of the structure was largely wood and paper, save for the 180-pound explosive and tiny, two-stroke engine. To “program” the Bug, its operator would factor in the range and direction it must fly, as well as winds aloft, to calculate the number of engine revolutions needed to take the Bug to its target. The aircraft was launched from a track on the ground, and after the engine reached the programmed number

of revolutions, its engine turned off, its wings disconnected, and the fuselage—carrying the warhead—dropped to the surface. Flight tests during the war demonstrated problems with the guidance system, but the Bug’s last flight in 1919 saw a successful 16-mile flight and impact. Although Kettering Bugs did not reach the front line in time to see combat, they paved the way for future uncrewed aircraft.

The Dawn of Human-Controlled Drones: Radio-Controlled Warbirds

As WWII drew toward its closing stages, Gen Eisenhower designated German V-1 and V-2 missile sites priority targets for the U.S. Army Air Force in Europe. Generals Spaatz and Arnold looked to develop a way to destroy these small, well-defended targets that was less costly, less risky to crews, and more precise than formation bombing. Building on the success of radio-controlled target aircraft from earlier in the war, the U.S. Army Air Force embarked on Operation Aphrodite, which stripped battle-worn bombers at the end of their life and outfitted them with radio control equipment and nearly 20,000 pounds of explosives.⁷ These bombers would take off with a human pilot and engineer at the controls, who would then bail out of the aircraft at about 2,000 feet and turn control over to a connected “mothership” bomber that would fly the drone the rest of the way to its target. Although innovative, Aphrodite missions were high-risk, and not one destroyed its intended target.

Radio or remote-controlled warbirds came into their own after the war’s end when they were used to measure radiation levels in nuclear clouds. In 1946, Operation Crossroads flew formations of over 50 radio-controlled B-17s and F-6F Hellcats to monitor nuclear bomb tests in the Pacific. The Hellcats launched from carriers and the B-17s from runways under remote control—a significant improvement over Operation Aphrodite’s bail-out method. The aircraft were outfitted with radiological sampling equipment and photographic suites to fly through radioactive clouds to collect data, controlled by airborne B-17 and F-6F motherships operating from safer distances. All the aircraft would then recover to an airfield. The 1948 Operation Sandstone nuclear weapons tests also employed line-of-sight radio-controlled B-17s, while other tests in the 1950s used jet-powered F-80 Shooting Stars converted in the same way.



Figure 1: A Firebee is launched as a target in an air-to-air combat training exercise in 1982

Source: U.S. Air Force Photo

These postwar radio-controlled systems proved that aircraft could be flown and provide meaningful mission effects without human aircrews in the cockpit.

The BQM-34 Firebee and Model 147 Firefly/Lightning Bug

In the late 1950s, Ryan Teledyne developed the high-speed, maneuverable BQM-34 Firebee as a target drone for air-to-air missile tests. The Firebee target drone was dropped from a larger aircraft or rail-launched with rocket assistance, then remotely controlled from either a ground station or a modified C-130 cargo aircraft mothership. A successful target drone, the Firebee was reliable, rugged, and agile, and it could pull up to 7 Gs at speeds over 0.9 Mach.

The Firebee also proved to be adaptable. In response to the very capable Soviet SA-2 surface-to-air missile system, the Air Force's "Big Safari" program developed several different reconnaissance variants of the Firebee. Usually air-launched from a C-130, they could be remotely controlled via a line-of-sight datalink, but they were more frequently pre-programmed to fly complete ingress and egress routes at planned altitudes without human guidance using a gyrocompass internal navigation system and later a doppler radar.

The family of Firebee reconnaissance drones was used for "dumb" and "dangerous" missions that were too risky for human pilots and did not require real-time decision-making, maneuvering, or modification.⁸ The Firebee and its siblings, Fireflies and Lightning Bugs, flew nearly 3,500 sorties from 1964 to 1975 over North Vietnam in high-threat areas and during inclement weather.⁹ They could get in, collect intelligence, and get out of environments where crewed aircraft could not safely operate. Still, operators had to await the aircraft's return before they could collect and process the intelligence. These drones proved that uncrewed aircraft had value in contested battlespaces and could fill mission areas that were too high-risk for crewed aircraft, even if they had no "real-time" interaction with human warfighters executing their missions.

The Beginning of Teaming Operations: Predators and Reapers

The General Atomics RQ-1 Predator broke these paradigms. While Predators were first developed for reconnaissance missions, a crucial innovation gave Predators the ability to send back real-time video to their crew, which enabled them to be far more operationally responsive and tactically relevant than Firebees, Bugs, and other early drones.¹⁰ As Predators evolved to use a satellite-based datalink that allowed controllers stationed hundreds or even thousands of miles away to operate its flight controls, sensors, and even launch weapons, the Air Force found that General Atomics had created an operationally responsive, remotely piloted aircraft (RPA) that could perform more than dumb, dangerous, or dirty missions.

The combination of the Predator's real-time video feeds, control systems, and long endurance enabled far more dynamic and complex intelligence, reconnaissance, and surveillance (ISR) missions, and arming the aircraft with the Hellfire and other weapons further increased their operational utility. MQ-1s and the follow-on MQ-9 Reaper aircraft could be used to launch timely and difficult strikes against time-sensitive targets as well as cue piloted aircraft strikes, including using a laser to designate targets for F-16s and

F-15Es carrying laser-guided bombs. The MQ-9 has proven extremely valuable and lethal when integrated with manned aircraft, and the MQ-1/MQ-9 strongly enhances overall mission outcomes.¹¹ Thousands of Predator missions flown in Operations Enduring Freedom, Iraqi Freedom, and Inherent Resolve demonstrated the ability of humans in the battlespace to dynamically team with piloted aircraft, pointing the way to future human-machine teaming.¹²

Having humans fly MQ-1/MQ-9s and operate their sensors and weapons—even remotely—has proven to be a critical means of responding to tactical opportunities and emerging situations in ways that automated, pre-programmed drones cannot. But large-scale RPA operations also place an extremely heavy burden on Air Force manning, and their dependence on satellite communications presents a potential liability as adversaries field spectrum denial, datalink intrusion, and anti-satellite capabilities. Fortunately, the miniaturization and growing power of data processing, advances in software, and development progress in artificial intelligence and machine learning (AI/ML) create the potential to shift from remotely piloted drones to a new generation of “smart” uncrewed collaborative combat aircraft using autonomous functions that can team with warfighters.

Why the Collaborative Combat Aircraft Imperative?

The Air Force is at a precarious point in its 75-year history due to decades of modernization neglect by the DOD and underfunding. It is now the oldest, smallest, and least ready in its history.¹³ As a result, it must now dramatically alter its force design to deter, and if necessary, defeat, great power aggression even as it struggles to meet its global operational requirements with a force that is too small and too old. Prolonged high-tempo counterterrorism and counterinsurgency operations since 2001 have placed immense pressure on the service, resulting in declining aircraft mission capable rates and soaring operation and sustainment costs.¹⁴ Demands on the Air Force have not diminished. Combatant commanders are increasingly asking for Air Force capabilities, now more than ever, to respond to the aggressive actions of China and Russia. The perfect storm of declining Air Force readiness and high operational demands

is further amplified by the fact that three decades of deferred modernization have heavily taxed the Air Force's ability to prepare for high-end conflict.¹⁵ The issue is not simply that the Air Force does not have the capacity to fulfill its obligations. Chinese capabilities and warfighting strategies now present unprecedented challenges to the U.S. military's legacy capabilities and operational concepts. In short, the Air Force must grow in capacity even as it dramatically alters its force design to counter adversary strategies and strengths.

Combatant commanders are increasingly asking for Air Force capabilities, now more than ever, to respond to the aggressive actions of China and Russia. The perfect storm of declining Air Force readiness and high operational demands is further amplified by the fact that three decades of deferred modernization have heavily taxed the Air Force's ability to prepare for high-end conflict.

The Air Force is committed to developing collaborative combat aircraft to help address these challenges and transform the Air Force's force design into one that can win. According to Lt Gen Clinton Hinote, Deputy Chief of Staff for Strategy, Integration, and Requirements, "It is clear that the autonomous collaborative platforms, we like to call them, or uncrewed systems, are going to be a major part of the future of warfare."¹⁶ Former commander of Air Combat Command, Gen Herbert "Hawk" Carlisle echoed Hinote's vision: "This is a natural evolution, especially when you look at the capability today with respect to AI, with respect to systems, with respect to the computing power and capability you can put in a particular size."¹⁷

Thirty Years of Pursuing a Smaller, More Efficient Force Has Yielded a Force Design That Loses

At the core of this challenge is a mismatch between the *U.S. National Defense Strategy* and the Air Force's capacity to meet it. Though the 2018 and 2022 *National Defense Strategies* both identify China as DOD's pacing threat, the U.S. Air Force is the smallest, oldest, and least ready in its history and lacks the capacity needed to deter or win in a high-end peer conflict. Importantly, decades of focusing on low-intensity conflicts in the middle east have left major force structure gaps in multiple Air Force mission sets. As just

one example, no capability exists in the Air Force or elsewhere in DOD that can perform penetrating counter-air missions in highly contested environments over very long ranges. If the United States is to dissuade, deter, or defeat an emboldened China, then the Air Force must grow in its capacity for this and other missions as it modernizes its force design and operational concepts for high-intensity, peer conflict.¹⁸

How did the U.S. Air Force get here? During the Cold War, the United States could not compete with the Soviet Union's sheer military mass, so it was driven to find other areas of competitive strength. Defense leaders pursued advanced technologies like the global positioning satellite system (GPS), precision-guided weapons, and stealth to secure an advantage, which enabled their smaller force to effectively counter the technologically inferior albeit larger Soviet Army.¹⁹ Even so, defense leaders at the time still sought to build as large a force as they could.

After the Soviet Union collapsed in 1991, DOD repurposed this approach to justify its budget and force cuts throughout the 1990s. Great power conflict was no longer the defining consideration of DOD's force design. Operation Desert Storm proved that a smaller force could overwhelm a numerically larger but technologically inferior military. This played an outsized role in shaping a new defense strategy that rationalized cutting existing forces under the new mantra of "smaller but more capable." In other words, this offset strategy was envisioned

Geography Drives Physical Aircraft Design

The defense community often views threat systems as the primary driver for aircraft requirements, but the physical geographies of a theater impose their requirements on aircraft design as well. An aircraft that must traverse the distance from Guam to the South China Sea must possess the range to do so. This imposes certain fundamental design choices on an aircraft. Importantly, no one aircraft can be optimized for every performance parameter. Engineers must make tradeoffs among attributes such as speed, maneuverability, endurance, range, payload, signature, sensor packages, size, engines, electrical power generation, cooling, and so forth. An airliner can efficiently carry a lot of people and cargo a long distance, but it can't fly high, fast, or win a dogfight like a fighter. Optimizing an aircraft design for its mission and physical environment dictates these physical attributes and tradeoffs.

as using advanced technologies to mitigate the risks of an out-numbered force, but in the post-Cold War period, advanced technologies became part of the reason why the force *could* become smaller. With no credible threat at the time to compel the DOD to think otherwise, this capability-based strategy seemed appropriate.²⁰

This perspective lasted well beyond its "safe to use" expiration date. Even in 2014, then-Air Force Secretary Deborah James claimed that the Air Force would continue to get smaller as it became "more capable."²¹ Given decades of inadequate budgets, the Air Force curtailed procurement of new capabilities and cut existing aircraft inventory in favor of upgrading and pursuing service life extensions to existing systems. Despite a handful of high-profile recapitalization programs, the Air Force acquired too few advanced aircraft over the last 30 years. Today, fully 84 percent of the Air Force's aircraft inventory was designed before the end of the Cold War for a very different set of threats than now exist in the Indo-Pacific and in Europe.²² Upgrading the Air Force's legacy aircraft has enabled them to remain effective, but only in regional contingencies that are conducted in permissive operational environments. Most of the Air Force's inventory remains vulnerable to modern air defense systems.²³

In short, the Air Force's smaller force may be efficient and cost-effective for low-intensity contingencies, but it does not have the resilience or degree of survivability needed to prevail in a highly contested peer conflict. In their pursuit of this "smaller but more capable" lore, service leaders have created a brittle force that does not have the capacity to maintain a robust operational tempo, execute operations with sufficient concentration and mass, tolerate attrition, or present complexity to an adversary.

The Scale of Warfare with China in the Indo-Pacific Requires a Larger Air Force

Conducting high-tempo, large-scale military operations against China in the Indo-Pacific requires an Air Force with greater force capacity.²⁴ One of the reasons for this is the tyranny of distance in the Indo-Pacific that defense planners often reference, which means there are problems created by the very long transit distances and large combat areas of this vast theater. The simple explanation is that covering distance requires time. For instance, even at high subsonic speeds, aircraft would still take an hour to transit from Kadena Airbase in Japan to target areas located around Taiwan, and flights from Guam to Taiwan would take four hours. The time that it takes to get to the fight has a significant impact on the number of aircraft able to achieve and sustain high-tempo, large-scale operations. Without enough aircraft (capacity), commanders must either reduce their operational tempo or pause between attacks—both create opportunities for an enemy to gain and maintain an advantage. Very large combat areas also require more aircraft to create massed effects simultaneously in multiple locations. Without sufficient capacity, planners must choose between diluting their attack coverage or massing effects in one area while neglecting other areas.

In light of these truths, prioritizing defeating Chinese aggression in the Indo-Pacific as the pacing U.S. national security threat means that trading capacity for more capability is no longer a valid force design approach for the Air Force. It now needs more capabilities *and* capacity. No matter how technologically advanced a U.S. weapon system may be, the simple fact is that conflict in the Indo-Pacific demands sufficient quantity—and no aircraft can be in more than one place at one time. This is not a theater where the U.S. military can afford to be "smaller but better."

Augmenting piloted aircraft with more affordable CCA may be a crucial way for Air Force leaders to achieve the capacity the Indo-Pacific demands.

Augmenting piloted aircraft with more affordable CCA may be a crucial way for Air Force leaders to achieve the capacity the Indo-Pacific demands. Some industry studies have indicated that tethered CCA could increase a piloted formation at a ratio of six or seven CCA to one piloted aircraft. If CCA

are untethered—operating in support of the broader mission package and not dedicated to a single flight lead—these numbers could be much higher. Moreover, CCA that operate as a coordinated swarm might be treated as a single entity even if their numbers are much higher. Whether tethered, untethered, or swarmed, CCA hold the promise to be force multipliers for the future Air Force, providing the numbers needed to achieve high-tempo operations at the scale that the vast ranges of the Pacific demand.

System Confrontation in the Indo-Pacific Requires New Operational Concepts and a New Force Design

The Air Force must also consider *how* it fights and *what* it fights with if it is to survive and win in a conflict with China. Chinese military theorists and practitioners have closely studied U.S. operational concepts, technologies, and employment and developed a “System Confrontation and Destruction” warfighting strategy specifically designed to dismantle traditional U.S. military advantages.²⁵ The RAND Corporation summarizes this strategy as “a confrontation between opposing operational systems rather than merely opposing armies.”²⁶ Unlike maneuver or attrition warfare, systems warfare seeks to identify and destroy the key nodes and links of a belligerent’s military force to “disrupt, paralyze, or destroy the operational capability of the enemy’s operational system.”²⁷ Accordingly, “This can be achieved through kinetic and non-kinetic strikes against key points and nodes while simultaneously employing a more robust, capable, and adaptable operational system of its own.”²⁸ This was the approach employed by air planners to secure the most spectacular large-force military victory of the 20th Century—Operation Desert Storm.²⁹ Desert Storm is the conflict that China studied, learned from, and then spent the next 30 years building its military capabilities with a principal objective of precluding the U.S. military from applying these kinds of operations against them.

The U.S. Air Force must relearn the systems warfare approach that was so successful in building and executing the Desert Storm air campaign, as well as develop new operating concepts to fight and prevail against China’s systems-oriented warfighting strategy. Today, the Air Force must use its small numbers of extremely valuable weapons systems like F-22s and B-2 bombers in a predictable series of plays. This creates limited sets of lucrative targets for China’s military planners. Advanced datalinks and other information networks that U.S. forces have come to rely upon are also vulnerable to China’s systems-focused warfighting strategy. By disrupting information flows, denying command and control (C2), and kinetically targeting physical “nodes” of the U.S. information system, China intends to blind U.S. commanders and paralyze their operations.³⁰ All these challenges are major reasons for the Air Force to develop new operating concepts for conflict with China. This recommendation was mirrored by the 2018 Commission on the National Defense Strategy, which found that “the United States needs more than just new capabilities; it urgently requires new operational concepts that expand U.S. options and constrain those of China, Russia, and other actors.”³¹

The Air Force must pursue a new force design to overcome the tyranny of distance *and* counter China’s strategy of targeting U.S. forces as a system. This is precisely what the Air Force plans to do: Secretary of the Air Force Frank Kendall is rightly focused on transforming the Air Force into one that can credibly counter China. In this effort, the Air Force must not discount how increasing capacity can address both the physical challenges posed by the Indo-Pacific and the operational problems of China’s strategy of system destruction presents. The good news is CCA have great potential to transform the USAF’s force design and provide the necessary capacity to defeat Chinese aggression. CCA could also empower novel operational concepts, including concepts for teaming operations, that are needed to prevail in the most stressing and existential scenario facing our nation today—high-intensity peer conflict with China in the Indo-Pacific.

The USAF Force Design Attributes Needed to Prevail in an Indo-Pacific Conflict

The combination of China's systems warfare and the operational challenges posed by the geography of the Indo-Pacific makes it clear that the U.S. Air Force's current force design is inadequate. If the Air Force is to field a credible force structure to deter, deny, and prevail against China, it must be appropriately sized and have the right mix of capabilities to achieve the following objectives:

- **Tempo:** The Air Force must be sized to maintain a high intensity and pace (or frequency) of operations against a peer adversary. Sustaining a high operational tempo against any adversary is crucial for U.S. and coalition forces to gain and maintain the initiative throughout a conflict. High tempos apply offensive pressure on the adversary, putting them in a reactive role and preventing them from adapting to and countering U.S. operations. Operational pauses create opportunities for an adversary to regenerate and reconfigure its forces, complicating U.S. planning and operations. Without enough combat aircraft and other capabilities, U.S. commanders will have to choose between spreading their forces thin at the risk of losing the ability to achieve enough mass to create desired effects or slowing their operational tempo to the point it creates advantages in time for an adversary. They cannot have both high tempos and sufficient mass without capacity.
- **Mass:** The Air Force must have the capacity to concentrate its forces and effects to achieve mission objectives and overwhelm an adversary's ability to defend. Capacity ensures that U.S. forces can generate desired effects against any adversary target. A force that is too small will be spread too thinly and cannot mass effects to achieve operational objectives: the adversary will either be able to successfully defend against or resiliently withstand the attack. Thus, insufficient mass can result in significant combat losses to U.S. and coalition forces or adversary adaptation. The demand for mass also highlights the need for survivability and lethality—none of these attributes alone are sufficient. Of these attributes, however, capacity is absent from the current U.S. Air Force force design. The scale of combat operations in the Indo-Pacific requires much larger numbers of forces than the Air Force currently possesses to prevent the dilution of effects.
- **Attrition Tolerance:** The Air Force must have the capacity to continue effective combat operations (with high tempo and mass) even while absorbing combat losses of weapon systems and operators over time. A military needs numbers to ensure sufficient depth of force to withstand attrition over time. Combat losses are a fact of peer conflict. As a force takes combat losses, it must have the reserve capacity available to “feed the fight” or continue to field forces forward to maintain pressure on the adversary. Doing this with sufficient forces avoids disrupting planned operations and derailing the larger campaign strategy. If a force does not have this tolerance, any attrition will degrade its ability to prosecute effective combat operations with tempo and mass. Today, the Air Force is extremely fragile and unprepared in this regard.
- **Strategic Reserve—Pilots:** The Air Force must be able to rapidly replace or otherwise compensate for combat losses of skilled and experienced warfighters. The skill and experience of a pilot corps are crucial to sustaining effective operations for the duration of conflict. Inexperienced pilots may not accurately interpret the battlespace and may lack the judgment to make the best decisions or take actions critical to mission

success. Worse, inexperienced pilots historically suffer higher attrition rates. Replacing combat losses with the right ratio of experienced warfighters is crucial to the long-term success of a conflict, and this relies upon the ability to produce and absorb new pilots at a meaningful rate.

- **Strategic Reserve—Aircraft:** The ability to replace aircraft at a rate that meets or exceeds their loss rate. An intense or prolonged conflict may exceed the strategic reserve of a military, requiring the nation’s industry to produce replacement aircraft that, at a minimum, meets the rate of loss one-for-one. If a nation entered a conflict with an already undersized force, this production rate must exceed combat losses and accommodate the excess required to train the demand for additional and replacement pilots. The ability to surge production requires facilities, raw materials, sub-tier suppliers, engineers, and a skilled workforce to quickly mobilize in relevant timeframes to prevent attrition from depleting reserve forces. This industrial capacity no longer exists in the United States.
- **Operational Resilience:** The ability to withstand combat losses and still effectively execute the mission in real time. Operational resilience requires capability redundancy in mission compositions, such that real-time combat losses do not collapse the mission into failure. In past conflicts, this kind of resilience implied the need to consolidate and maximize the sensors, avionics, and weapons onboard a single aircraft such that it could independently close a kill chain. Operational resilience in future conflict will still require these aircraft, but it will also demand the disaggregation and distribution of the kill chain and other functional “nodes” throughout the mission package. This layered redundancy creates targeting complexity for the adversary that resists system destruction. DOD’s focus on creating an “efficient” force has created an Air Force that is too small and brittle to have this kind of operational resilience.
- **Operational Complexity:** The ability to present uncertainty to the adversary through surprising and confounding mission compositions. Mission compositions should be of such complexity, redundancy, and resiliency that they frustrate the adversary’s ability to map the system relationships and dependencies and complicate targeting plans. Operational complexity presents numerous dilemmas to Chinese commanders, countering their system destruction strategy by making it difficult to determine how to collapse U.S. operational systems. Until recently, technological limitations made this kind of system complexity too unwieldy and overly complicated to implement. New network architectures, software, artificial intelligence, and mesh networks can now provide the interoperability necessary to enable systems of this kind of complexity, offering a means to side-step China’s system destruction strategy.

Collaborative Combat Aircraft Can Solve Gaps in the U.S. Air Force’s Force Design

Recent advances in micro-processing, datalinks, software programming, and autonomy have created the opportunity to field teams of collaborative combat aircraft that can solve major gaps in the Air Force’s force design, multiply the combat power of its mission packages, and counter China’s system destruction strategy. CCA will also be able to execute mission-essential roles, maintain high levels of execution through attrition, increase complexity, and impose cost on an adversary. For CCA to do these things at scale, they must be designed to operate

Mosaic Warfare Disaggregates the Force to Complicate the Adversary's Problem

Mosaic Warfare is a warfighting theory and force design that exploits networking and datalinks to create customized mission packages that act as a system of systems. Mosaic treats platforms as individual nodes of the kill chain. By fielding large volumes of redundant nodes, Mosaic seeks to create complex and resilient kill webs that withstand an adversary's attempt to collapse the system.

objectives. Human intuition, cross-domain thinking, and intelligence will remain essential to mission success, and partnering with CCA could allow humans to focus on critical cognitive tasks of decision-making, dealing with unforeseen events, and otherwise managing battlespace operations.

Human-CCA teams can also reduce risks to humans, increase the potential to create war-winning mission effects, and disrupt an adversary's warfighting strategy. Because planners and mission commanders can accept higher CCA losses, they can think differently about the risk tolerance these systems can provide. Teamed with crewed aircraft in force packages, collaborative combat aircraft can be employed in ways that increase the potential for mission success. For instance, CCA could increase the survivability of their crewed teammates by acting as decoys or "missile sinks" that soak up enemy air-to-air or surface-to-air missiles as a means to alter kill-exchange ratios. CCA losses in combat should not have as dire an impact on specific missions, the long-term viability of the force, or the overall campaign because they are more easily replaceable than experienced human combat aircrews. The attrition tolerance that CCA offer may have the added benefit of imposing cost on the adversary, an important feature in any competitive strategy.

Getting CCA right matters: teaming with humans in spectrum-contested battlespaces will enable the Air Force to scale in ways that will be essential to future warfare.

Another unique attribute that CCA can bring to the attrition equation involves reducing the impact of losing highly experienced aircrew. An underappreciated problem of combat attrition is the loss of experience in the front-line force. By absorbing losses, CCA forces can protect experienced human warfighters that often make the difference in operational and tactical outcomes. Moreover, when a CCA is lost, its replacement can be fielded with the exact same levels of competence because their skill is based on program updates, not personal and individualized history. Unlike humans who require years to train and develop experience, CCA agents are as skillful and able as their latest software download. So long as their software is up to date, a new CCA is just as useful as the one is replacing—there is no such thing as a CCA "new guy."

without the control stations, manpower, and bandwidth requirements of today's remotely piloted aircraft. This means that uncrewed aircraft must be effective in complex environments without the need for direct human control of the aircraft flight systems or sensors. In short, getting CCA right matters: teaming with humans in spectrum-contested battlespaces will enable the Air Force to scale in ways that will be essential to future warfare.

CCA will also give the Air Force opportunities to create new operational concepts for their use that transcend traditional dumb, long-duration, dangerous, and dirty uncrewed aircraft missions. The right operational concepts could enable CCA and crewed aircraft to bring their respective strengths to achieve mission

Costing Crewed and Uncrewed Aircraft

The defense industry has long had a rule of thumb that airplanes have a “dollar per pound” cost. This rule of thumb has held true because it accounts for raw materials, production labor, number of engines, and system complexity, all of which increase with the weight. Acquisition strategies like quantity, rate, and multi-year buys often only marginally impact unit price. Thus, an aircraft that is larger due to range, fuel, and payload requirements will cost more than a smaller aircraft. Aircraft designed for the Indo-Pacific will have to be larger just to go farther, and this will drive the inherent cost of these aircraft up. Highly advanced systems, sensors, processors, and intensive software packages of modern aircraft are further distorting this long-held cost estimation technique. Other costing factors include building multi-role aircraft versus single-role aircraft and service life.

Autonomous teaming aircraft will not be immune to these factors. If an autonomous teammate must go the distance in the Indo-Pacific, there will be certain design attributes—and, therefore, costs—that cannot be avoided. These built-in design costs may be the reason why Secretary Kendall has recently moved away from providing the B-21 a teammate: “The idea of a similar range collaborative combat aircraft is not turning out to be cost-effective.” If the Air Force is looking to CCA to solve capacity shortfalls through affordability, then it must seek to break the cost curve in other ways while also meeting the physical requirements of the mission and role. Limiting the system complexity of the CCA, the number of onboard mission systems, service life, and changing employment concepts may be useful approaches to bringing costs below those of crewed aircraft while ensuring they also have the physical design attributes demanded by the battlespace.

Planners can also use the autonomous competence of CCA to increase complexity in the battlespace. “Mosaic-type” force compositions could use CCA to disaggregate mission forces and field redundant nodes to create broad and resilient kill webs. The Department of the Air Force’s Scientific Advisory Board is investigating options for CCA with “a distributed, mission-tailorable mix of sensors, weapons, and other mission equipment” to be part of the NGAD family of systems.³² Such mission packages could present targeting conundrums to the adversary and simultaneously augment crewed aircraft to deliver operational tempo and mass. Dr. Tim Grayson, Special Assistant to the Secretary of the Air Force and former director of DARPA’s Strategic Technologies Office, explained how the Air Force is just beginning to explore new ways to employ CCA:

You might take a CCA platform capability inspired by some of the NGAD work, but not deploy it with an NGAD. It might actually be launched and, at least for initial deployment, operated by some other additional entity. And then, later on in the fight, reform a new formation ... reform even a new team, where you know the command and control might fall over to a different platform. We’ve seen some of this in some of the studies that have been done between NGAD and B-21 ... where there could be a little bit of ... dynamic mix and match of who’s going to form the offensive line, so to speak, and who’s going to be the quarterback.³³

A key to gaining the operational benefits of collaborative combat aircraft will be to field them in quantity. While affordability should not be the overriding goal of any force design, it is an enabler. In the case of CCA, they

must be able to achieve the lower cost targets that will allow their procurement at scale even in a time of fixed budgets. Because these aircraft are uncrewed and will be used differently than crewed mission aircraft, there are opportunities to change traditional aircraft design and construction methods in ways that reduce their cost. Air Force leaders and other policymakers in the DOD should question their traditional assumptions for combat aircraft cost estimates and explore ways that CCA can be developed and acquired that flip the cost imposition equation.

The Air Force hopes that uncrewed autonomous aircraft will allow it to affordably achieve its future force design. And, according to Secretary Kendall, “It is reasonably clear to me that we are poised to go ahead and take a significant step forward in that area ... I don’t know exactly how long a step that’s going to be, but I’m determined to make it.”³⁴ Employing collaborative combat aircraft at scale may address many of the force design imperatives that the Air Force must meet to counter and prevail against a peer adversary. Given how mismatched the Air Force’s force design is for systems warfare with China, CCA cannot be fielded fast enough.

The Current State of CCA Development

Autonomous aircraft teaming has been a top research, development, test, and evaluation (RDT&E) priority for the Air Force for years. In 2019, the service published a *2030 Science and Technology Strategy* that identified complexity, unpredictability, and mass as crucial features for any future force design to establish a strategic advantage over adversaries. More specifically, this strategy described how the Air Force could augment its “high-end platforms with larger numbers of inexpensive, low-end systems” that could perform as swarms of low-cost, autonomous aircraft.³⁵ The Air Force Research Laboratory (AFRL) subsequently designated Skyborg, an autonomous aircraft teaming architecture, as one of three initial Air Force Vanguard programs. These programs are designed to rapidly develop and deliver new technologies to warfighters.³⁶ CCA will also be key elements of an NGAD family of systems, augmenting operational missions as agents that can “serve as decoys or scouts or even jam enemy signals or conduct their own strikes.”³⁷

This flurry of research and development programs across the Air Force, DARPA, and the defense industry are intended to create a future force of collaborative combat aircraft at full throttle. Programs like AFRL’s Skyborg, DARPA’s Air Combat Evolution (ACE) initiative, and industry efforts such as Lockheed Martin’s Have Raider I and II and Boeing’s MQ-28A Ghost Bat are generating enthusiasm over the maturity of autonomous combat aircraft. Air Combat Command has even awarded a contract to Blue Force Technologies for an autonomous adversary aircraft, a move that would seem to take CCA out of the research and development realm and into the very real world of operations. Air Force Secretary Frank Kendall has fueled this fire by weaving CCA into his seven operational imperatives, which are intended to address major gaps in the Air Force’s capabilities to fight a war with China.³⁸

CCA Development Programs

The Air Force’s Skyborg program has been its premier Vanguard effort for developing CCA. Skyborg’s objective is to create a common autonomy “architecture” for CCA upon which future autonomous capabilities can be built.³⁹ Skyborg is creating an open mission architecture and developing a modular and universal “core” autonomy control program that can control any host aircraft. Called the Skyborg System Design Agent (SDA), this baseline universal autonomous aircraft control software could accelerate the development and fielding of multiple CCA variants while decreasing their costs. The Skyborg SDA should easily integrate sensor management software and mission functionality across different aircraft types.⁴⁰ The Air Force selected the General Atomics MQ-20 Avenger and the Kratos XQ-58A Valkyrie to fly the Skyborg SDA, and both have had successful test flights. General Atomics flew two Avengers—the largest aircraft to fly with the Skyborg SDA—on a multi-hour flight.⁴¹ The most recent Valkyrie missions expanded the Skyborg SDA’s flight envelope.⁴² Regardless of this progress, Skyborg’s potential to develop a common autonomy architecture will be limited by the fact that it is neglecting to address human teaming dynamics.

Should Collaborative Combat Aircraft be Tethered or Untethered?

In tethered operations, the CCA would operate with dedication to a single crewed platform. This concept is often referred to as a “loyal wingman” because the CCA would function as a member of a coherent team that shares a discrete mission objective and act under a hierarchy of authority within the formation. Tethered CCA might fill roles such as a weapons truck, dedicated electronic warfare platform, or a stimulant to a radar site as part of a “wild weasel” team conducting suppression of enemy air defenses.

Untethered operations, by contrast, would operate independently of any crewed aircraft or formation. As mission support aircraft, untethered CCA's capabilities would be prioritized for the greatest good of the mission package but are not beholden to any single formation within that package. Untethered CCA have more flexibility with respect to the types of capabilities it can introduce. Unlike tethered operations, which would be limited in number and scope, untethered CCA are more likely to compose large swarming formations, multi-axis electronic warfare networks, large-area distributed sensing fabrics, or initial sweeps of offensive counterair. In this concept of operations, an air battle manager would direct the CCA based on mission objectives, mission phases, threat behaviors, and requests from crewed aircraft. However, because the untethered CCA is not dedicated to any particular crewed aircraft, requests for CCA support may be denied in favor of other priorities.

The answer to the question of “tethered or untethered” CCA is, most probably, that it depends. Untethered operations have the potential to present greater complexity to an adversary, enhance mission resilience, and provide greater operational flexibility. Tethered operations, on the other hand, can provide dedicated formation support, improve formation outcomes, and enhance individual formation effects. Both approaches have value, and each will look very different from the others.

Whether tethered or untethered, *how* these CCA will team with humans must be engineered from the beginning. As the Air Force and defense industry explore these concepts, they should also consider these important questions.

DARPA's Air Combat Evolution (ACE) initiative is also focused on developing and demonstrating the competency of autonomous software in combat environments requiring highly dynamic aircraft. By demonstrating that autonomy can be more proficient than humans in these scenarios, DARPA program managers hope to dispel perceptions that uncrewed aircraft agent sensing and control are too slow to safely and effectively fly in one of the most stressing of aerial missions: dogfighting. According to Col Dan Javorsek, the commander of the U.S. Air Force Operational Test and Evaluation Center at Nellis Air Force Base and former DARPA program manager, DARPA structured its “Alphadogfight” trials to “demonstrate trusted, scalable, human level, AI-based and AI-driven autonomy for air combat.”⁴³ The final gauntlet for Alphadogfight was a contest between the AI and a human F-16 pilot flying in a simulator. In all five simulated dogfights, the AI bested the human fighter pilot.⁴⁴ This simulation showed the ability of an autonomous agent to successfully maneuver in a complex scenario—an important step in building trust with humans, but this was totally independent of any teaming behaviors.

The second phase of DARPA's ACE program will progress past simulation by hosting the AI control agent in an L-39 Albatros aircraft to test its ability to execute flight tasks in the physical world while safety pilots monitor its behavior.⁴⁵ Both phases of the ACE program correctly identified that humans must be able to trust CCA to conduct "complex combat behaviors" in order to progress to the kind of "hierarchical framework" that would define human-CCA interactions.⁴⁶ To support his objective, technical efforts appear to remain focused on building human trust through consistent and dependable autonomous maneuvering. Like the Skyborg Vanguard program, what is missing in these efforts is developing the teaming interactions between humans and their CCA.

Lockheed Martin's Have Raider I and II demonstrations also sought to display the ability of an AI-controlled aircraft to navigate credibly through a dynamic environment. According to program manager Shawn Whitcomb, Have Raider "put a fully combat-capable F-16 in increasingly complex situations to test the system's ability to adapt to a rapidly changing operational environment."⁴⁷ In its first demonstration, the AI-controlled F-16 flew in formation with its crewed flight lead, executed a strike, and then rejoined the formation of the human-piloted aircraft. In the second demonstration, the Have Raider AI autonomously responded to its changing threat environment during an air-to-ground strike mission. Tactical tasks included avoiding pop-up threats and rerouting to the target.⁴⁸ Still, this demonstration follows traditional patterns of focusing on the performance of the autonomous vehicle to the neglect of exploring the challenges, demands, and needs of integrating human teaming into the mission.

Less is known about the technological progress of Boeing's MQ-28A Ghost Bat, Australia's Loyal Wingman pathfinder. While Australia's declared intent is to use the Ghost Bat to "investigate factors such as the level of automation and autonomy, use of artificial intelligence, and human-machine teaming concepts," Boeing program managers appear to have a much broader vision for their uncrewed system.⁴⁹ According to Jared Hayes, Senior Director of Autonomous Aviation and Technology, and Dr. Shane Arnott, Program Director of Airpower Teaming Systems, Boeing will use the three Ghost Bats built thus far to prove "the entire system, which is much more than just an airframe. It includes user command interfaces, modular sensor packages, maintenance regimes, datalinks, and of course, software."⁵⁰ The Ghost Bat completed its second phase of basic flight test series in late March 2022.⁵¹

Although it seems clear that autonomous aircraft are still somewhat nascent technologies, the Air Force's Air Combat Command is eager to use them in an adversary aircraft (also known as "red air") role for training purposes. Air Force fighter squadrons have long supplied their own red air training, but their geriatric aircraft, low availability rates, and high cost-per-flying-hour are straining the viability of this approach. Given that the hours available for any Air Force squadron to fly are constrained by a fixed budget, each red air sortie takes away from other operational training. Even at Nellis Air Force Base, which hosts the nation's premier combat training exercises, legacy aircraft cannot provide viable fifth-generation threat presentations, and the Air Force's F-22 and F-35 inventories are too small to fulfill the adversary role. Fielding autonomous uncrewed adversary stealth aircraft could free up these high-value fifth-generation aircraft for other, much-needed training activities. To that end, Blue Force Technologies is developing a stealth UAV to imitate fifth-generation enemy aircraft for beyond-visual-range engagements with crewed

fighters. An important caveat is that Blue Force Technologies is only responsible for developing the airframe. The path for integrating an AI control agent, mission systems, and sensors is still unclear, and it will *not* include any kind of human teaming employment operations.⁵²

AFRL's Off-Board Sensing Station (OBSS) developmental aircraft effort also has the potential to move beyond its demonstration phase. AFRL's statement of objectives indicates the program is intended to "develop and flight demonstrate an open architecture aircraft concept to achieve the goals of rapid time-to-market and low acquisition cost [through an aircraft that] will be designed for limited life in terms of years, not decades, with no depot maintenance and limited field maintenance considerations."⁵³ Awarded to both General Atomics and Kratos, the OBSS contract is a year-long program that comes with options to continue Skyborg's technical development.⁵⁴ While it is unclear exactly what AFRL's cost targets are, this concept is well-aligned with the Air Force's affordability and speed-to-field objectives needed to achieve capacity. This approach could break current costing paradigms that limit aircraft production quantities and make CCA a real option for the service's future force design. Still, if OBSS continues the same technical priorities as Skyborg, it too risks neglecting the needs of human teaming in its development.

Developing CCA mission functionality absent robust human teaming information can lead to CCA software cores that are insufficiently responsive to humans or are simply too difficult to interact with. The answer is to engage real warfighters in the development of CCA so they will have the teaming processes and technologies that will make them game-changers in peer conflicts.

Teaming, The Critical Missing Ingredient in Current CCA Development

Secretary Kendall expressed confidence that "there's enough technology in existence from [CCA] programs that we've already conducted, it convinces me that's not a crazy idea."⁵⁵ He further asserted, "It is reasonably clear to me that we are poised to go ahead and take a significant step forward in that area."⁵⁶

Despite Kendall's eagerness to talk about "a formation of a crewed aircraft controlling multiple uncrewed aircraft," the developmental focus for ongoing efforts has almost exclusively been on removing the direct pilot control from the aircraft and demonstrating the ability of the CCA to autonomously fly safely, navigate, maneuver in formation, and execute specific mission tasks.⁵⁷ Autonomy development has focused on breaking missions down into discrete tasks that can be programmed and layered in the CCA autonomy agent. Engineers have had to tackle the basic problems of uncrewed aircraft takeoffs and landings; real-time navigation; ground avoidance; flight performance envelope adherence; and dynamic, tactical maneuvering. The results have been impressive. Simulations of autonomous aircraft, even large swarms, have shown their ability to "sense" threats and respond to changes in the battlespace or injects from humans.⁵⁸ These tasks are clearly foundational to making CCA operational, fielded capabilities, and they are all the more challenging because CCA must be able to respond to changing environments and stimuli.

These priorities are not misguided. Indeed, creating autonomy that is capable of mimicking human performance in the demanding battlespace environment is the first step to making CCA a viable capability. However, key teaming considerations—how these CCA will integrate and operate *in collaboration with humans*—are not sufficiently included in any of these programs. As important as the Air Force, DARPA, and defense industry’s efforts are, developing mature CCA also requires developing an understanding of teaming interactions between CCA and their human teammates. This is a crucial step toward creating CCA autonomy software that is capable of effective, efficient collaboration with human teammates. Providing injects to test a CCA’s response is fundamentally different from the interactive give-and-take flow of information that comprises real collaboration between uncrewed and crewed teammates. One recently retired Air Force official familiar with the Air Force’s CCA portfolio and defense industry efforts stated that there are few CCA efforts that include teaming as a key pillar of research.⁵⁹

Involving Air Force warfighters in every step of CCA development—including in the development of their autonomy agents—would be a major step toward resolving this shortfall. Teaming is not merely an issue of determining the right datalinks and message formatting standards that can be bolted on after developing a CCA’s autonomous agent. While the teaming interactions and behaviors that must be built into CCA may appear extraneous or superfluous to the mission decompositions that engineers have conducted, they are, in fact, essential to the psychological and cognitive human factors of teaming. Developing CCA mission functionality absent robust human teaming information can lead to CCA software cores that are insufficiently responsive to humans or are simply too difficult to interact with. It can also increase warfighter distrust in their autonomous teammates. The answer is to engage real warfighters in the development of CCA so they will have the teaming processes and technologies that will make them game-changers in peer conflicts.

Without building human factors related to teaming into CCA programming from the beginning, the Air Force risks reducing their full operational potential in ways that may ultimately result in mission failures in combat. Without teaming as a deliberate line of technical effort that is co-developed with operators and integrated with their thought process, CCA will not fulfill the Air Force’s hopes that they can be true force multipliers. Collaborative combat aircraft will not be pre-programmed drones with fixed missions flying on autopilot, and these basic challenges are not yet entirely solved. In short, autonomous *technology* may be progressing, but autonomous *teaming* still has a long way to go.

Create Teaming Concepts That Maximize the Strengths of Both CCA and Piloted Aircraft

Will my CCA teammates enhance mission success? CCA effectiveness in combat will directly correlate with *how well they team with humans* in addition to their sensors, weapons, and other capabilities they carry. Yet the advantages autonomous CCA teammates will provide in the battlespace are still unclear since the Air Force has not sufficiently articulated or developed operational concepts that describe how CCA will operate, maneuver, and otherwise partner with humans. The Air Force must first understand the unique attributes and advantages of both CCA and humans and then develop teaming concepts of operation and tactics, techniques, and procedures that exploit their relative strengths. This will enable the Air Force to create human-CCA teams that complement each other and rely on teaming dynamics and behaviors that maximize their combined operational potential. Moreover, these behaviors must be

Effectiveness:

The degree to which the employment of collaborative combat aircraft and their integration with humans improves overall mission accomplishment and operational outcomes.

prioritized and programmed into CCA during their development because they are critical underwriters of CCA designs. Warfighters and their commanders will also need robust, real-world training to master CCA teaming operational concepts and develop confidence that CCA will provide a much-needed combat edge in highly contested battlespaces.

Identify the Relative Strengths and Weaknesses of Humans and Collaborative Combat Aircraft to Build the Right Human-CCA Team

As the Air Force conceptualizes CCA mission packages and operational concepts, it must consider its existing mission gaps, how CCA could fill these gaps, and the potential for CCA to create a complex system of systems that enhance resiliency in the battlespace while posing dilemmas to the adversary. A traditional force development approach might reduce both CCA and their crewed aircraft to a list of desired technologies, sensors, weapons, and effects. While these are relevant and important considerations for composing future mission forces, the Air Force must also examine the unique attributes that humans and CCA will bring to their collaborative operations. Deliberately constructing teams to leverage the strengths of humans and machines can maximize their relative operational value and mitigate their respective vulnerabilities.

The first and most obvious advantage that CCA offer combat operations is the removal of humans from the cockpit. This is often where force planners prematurely conclude their assessment of potential CCA advantages. The truth is that the unique advantages CCA can provide in the battlespace are not yet fully understood or well-articulated despite technical enthusiasm for CCA with AI/machine learning capabilities. On the one hand, human combat aircraft crews will likely continue to excel in higher-level cognitive tasks like

making decisions in unforeseen circumstances, innovating when faced with new scenarios, and prioritizing and reprioritizing actions in changing operational conditions. On the other hand, advances in micro-processor speeds, software programming, network technologies, sensors, and AI/ML enable warfighters to exploit CCA in new ways beyond “dumb, dull, dangerous, or dirty” mission sets. CCA might employ their AI/ML and advanced processing to provide earlier recognition of threat behavior patterns, then maneuver in ways that spoil an adversary’s targeting or develop real-time novel kill chains to side-step an adversary’s tactics and procedures. There also may be something unique about the form and function of future CCA that allow them to act in entirely different ways than manned aircraft. Whatever these attributes are, Air Force policymakers, technologists, and warfighters should collaborate to better understand the potential capabilities and limitations of CCA as well as the strengths and weaknesses of humans. This is a *fundamentally different approach* than simply determining how CCA could fill gaps in the Air Force’s future force design. Air Force leaders, policymakers, and force planners should therefore consider qualitative features when building human-CCA teams in addition to the operational effectiveness of their individual mission systems.

Develop Operational Concepts; Concepts of Employment; and Tactics, Techniques, and Procedures to Exploit Team Strengths

Although Air Force warfighters generally agree that autonomous CCA teammates could provide operational advantages in a peer conflict, many continue to question the nuts and bolts of *how* CCA will perform in contested battlespaces. For example, how could human-CCA *team* attributes help counter adversary threats, including their decision-making processes as well as their systems? How could CCA-hosted AI/ML identify an adversary’s behavior patterns in the battlespace to increase threat or target awareness, and how could they rapidly propose alternate flight paths to increase team survivability? Can swarms of CCA frustrate an adversary’s targeting, obfuscate the locations of friendly aircraft, or conceal friendly mission objectives? How could CCA be employed in ways that extend and slow an adversary’s decision processes, keeping them in a “paralysis of analysis” instead of acting?

Once policymakers and warfighters understand the respective attributes of human-CCA teams, they can begin to answer these questions and map how CCA should operate, maneuver, and partner with humans to achieve mission success. This understanding is the critical precursor for developing concepts and tactics, techniques, and procedures for human-CCA teaming operations that take full advantage of their respective attributes. Technical details like datalinks, message sets, sensor capabilities, operational flight programs, and other hardware and software features of teamed aircraft also matter when determining specifics for how human-controlled weapon systems and CCA must interact and operate together.

Warfighters, as well as technologists, must be included in the early stages of developing CCA and their teaming concepts since both communities will have different perspectives on these attributes and technical capabilities. Once warfighters understand the unique advantages of CCA, sharing their experience and creativity with technologists will be key to creating novel and effective combat operations and tactics. Moreover, experienced warfighters will also have first-hand knowledge of established operational concepts, employment, and tactics for traditionally manned weapon systems, which can be a solid starting point for

creating innovative human-CCA teaming operating concepts, tactics, techniques, and procedures.

Program Teaming Dynamics into CCA, Modeled on Proven Human-Human Combat Team Interactions

Human factors in teaming dynamics and protocols must take greater precedence in the development of CCA designs and software. Technologists must treat teaming as more than human inputs to the CCA, the technical information humans and machine share, and the datalinks they use. True collaborative teaming operations include behaviors like the give-and-take of roles and responsibilities across teammates as well as standard procedures, contracts, and formations. This will require technologists to account for human cognition, emotions, feedback loops, communication, trust, errors, and the many other interpersonal pieces of team dynamics as they develop CCA software and algorithms.

An effective way of doing this is to use insights from warfighters to inform CCA software and algorithm development and maturation. Although this relational human element can seem unquantifiable—or, as one autonomy engineer stated, “soft and fuzzy”—human-piloted aircraft formations are long-established, proven models for high-performing combat teams. By mapping the rules, norms, codes, contracts, interactions, and exchanges of human combat teams across different weapon systems, technologists can identify the behaviors they should mirror in human-CCA teams. Engineers can use these existing standards and dynamics as initial models for how to code for CCA interactions and behaviors with their humans. Again, accomplishing this “soft and fuzzy” task in ways that increase overall combat effectiveness will require the Air Force to take advantage of its experienced warfighters early and often in CCA development.

Build Mastery Through Continual Test and Training

Warfighters will need robust simulations and real-world flights to master CCA teaming concepts and tactics and develop confidence that CCA will provide a combat edge in highly contested battlespaces. While much of this can be done in simulation, warfighters need exposure and experience with CCA teammates in the real, physical world to build familiarity and trust and then master teaming operations. CCA must fly training sorties with average line pilots of varying skill levels and experience to prove their combat effectiveness, not just a small cadre of highly trained members of the operational test and evaluation community. If CCA are only effective in tightly controlled, perfect environments, they may not be reliable in combat. Warfighters of varying experience and abilities also must have the opportunity to mission plan, fly, and debrief with CCA on a regular basis, both to train the humans and to train the CCA. Because CCA will be part of future combat mission packages, flight training must be more frequent than the sporadic missile tests or live weapon drops that aircrews currently perform as part of their training.

The Air Force Warfare Center (USAFWC) is well-positioned to support this concurrent, continuous development, testing, and training. The USAFWC has the basing, ranges, and warfighter expertise that will be essential to developing, validating, and evolving CCA programming, teaming protocols, and human performance. By embedding government and industry engineers and technologists with warfighters at the USAFWC, the Air

Force can cultivate tight-knit, cross-discipline teams that iterate and improve CCA autonomy on a rapid feedback cycle. Relationships like these have precedent in other Air Force acquisition programs of record but typically are not formed until programs enter their engineering, manufacturing, and development phase (post Milestone B).⁶⁰ In these cases, the combined test forces are working together to test, work out bugs, and validate *already developed* software and hardware. CCA combined teams should use similar models as they concurrently work to explore, develop, and then refine CCA autonomy, a technique some in the defense industry call “fly-fix-fly.”⁶¹

Finally, the Air Force should rapidly acquire some number of early-generation CCA to provide operational warfighters with the means to conduct robust test and training missions that explore and refine operational concepts and tactics for their use.⁶² These initial aircraft could consist of small numbers of early “minimum viable product” CCA autonomous teammates that have the capabilities needed to support test, training, and other real-world developmental missions that will inform the maturation of increasingly capable CCA.⁶³

Recommendations for the Air Force:

- Identify the key relative strengths and weaknesses of humans and CCA to build the right human-CCA teams.
- Develop concepts of employment and tactics, techniques, and procedures to exploit these team strengths and mitigate their shortfalls.
- Program teaming dynamics into CCA, modeled on proven human-human combat team interactions.
- Build mastery through continual test and training.

Include Operators in CCA Development and Provide Them with the Tools They Need to Understand How CCA Will Perform in the Battlespace

Why did my CCA do that, and what will they do next? Autonomy and machine learning programs remain notoriously opaque. Even software developers that write the code may not fully understand how or why a machine learning agent creates certain outcomes.⁶⁴ Without an understanding of how CCA think, how they make decisions, and why they take certain actions, warfighters will be unable to anticipate how their autonomous teammates will react when given data and other inputs. This inherently creates a lack of trust that can stymie the effectiveness of CCA teams. Involving warfighters in CCA development would not only improve the ability of the engineers to hone their design but would also foster the warfighters' understanding of how CCA perceive, think, decide, and behave as they do. Just as pilots must understand the flight handling qualities and performance envelopes of their aircraft to maximize their employment, warfighters in CCA teams must understand their CCA's autonomous agent. Finally, involving warfighters in CCA development would also support the creation of explainable CCA technical orders, tactics manuals, and mission teaming tools that warfighters must have to optimize their employment of CCA in future operations.

The need to understand the tools of combat is not new, nor is the need to understand how other teammates in a formation or mission package will behave. What *is* unique is that CCA with autonomy will be both tools

Warfighter Applied Understanding:

The ability for a warfighter to comprehend and have insight into the “how” and “why” of their CCA outputs and behaviors and to know the performance characteristics, boundaries, and fragility of their CCA agent so that they can maximize CCA utility over the lifecycle of a mission.

and teammates. As tools, CCA are far more complex and enigmatic than any individual sensor, emitter, or weapon. As teammates, they cannot describe their “internal mind” or “thought processes” as a human teammate can, and therefore may behave in ways that may appear incoherent or unpredictable.⁶⁵ Warfighters need an applied understanding of their CCA agent from both tool and teammate aspects to effectively operate with them in the battlespace.

Involve Warfighters in CCA Development to Enhance Their Understanding of the CCA Agent

Warfighters should participate in shaping the logic, interaction, incentives, weights, and models of CCA autonomy so that CCA behavior in real-world operations makes sense to them. This means that engineers and technologists must collaborate with current and qualified operators to ensure that CCA autonomy is aligned with warfighter needs. CCA machine learning algorithms optimize very specific outcomes such as their fuel

burn rates, threat avoidance maneuvers, airspeed to targets, and so forth. These algorithms are layered with others and then embedded within traditional deterministic software to produce specific behaviors. Involving warfighters deeply in CCA development would improve their understanding of how CCA algorithms and programming layers interact to create CCA decision behaviors.

Operators should be involved in the CCA developmental process—ideally by embedding them in CCA development teams—not only to ensure their autonomous teammates perform actions as expected, but so the operators also understand and can explain the logic that underpins CCA behavior. Warfighters do not need to know every line of code or algorithm, but they do need to understand why and how their CCA agent functions and behaves as it does so that they can employ their CCA agent in ways that enable them to be more effective as a team. Warfighters that understand the autonomy’s internal processes and have the ability to describe “why” and “how” it performs in plain language can then act as ambassadors to their operational communities to translate CCA behavior into terms that are understood.

Develop Interactive Mission Tools to Support Continual Learning and Mastery

Humans will need robust mission planning tools to integrate their CCA into their operational plans. While many teaming tactics and roles will be standardized, humans will need to be able to adjust and customize CCA decision processes and behaviors to accommodate the specifics of a particular mission’s objective, threat order of battle, intelligence reports, risk levels, and commander intent. They must also be able to identify contingency plans, including what many warfighters call “audibles”—deviations from the plan that are communicated in real time. Moreover, as humans learn more about the unique attributes of CCA, there may be other elements that they seek to adjust for the mission. All of these are important elements of mission planning.

Air Force warfighters already have well-established processes to increase their effectiveness in the battlespace aided by software tools that encompass the entire lifecycle of a mission, from mission planning to mission rehearsal and post-mission debrief. The Air Force should integrate CCA teammates into these processes to enable mission commanders to compose a mission package and select and customize tactics, simulate the intended game plan against anticipated threats, and otherwise test and adjust the mission plan. Doing so is a critical component of ensuring the effectiveness of CCA teams.

Mission rehearsal tools are likewise important in testing CCA programming prior to mission launch. These simulations will allow humans to check the validity of their CCA programming, catch and correct errors and omissions, or even explore alternatives to optimize their performance in different scenarios. High-fidelity mission rehearsal tools may offer the opportunity to experiment with new tactics and CCA agent programming, provide the CCA agent repetitions, or even harvest insights from the CCA agent that might suggest alternate game plans or other valuable knowledge.

Finally, CCA should be incorporated into post-mission debrief processes. Debriefs that review every element of a mission, from the beginning of mission planning to the post-landing maintenance summary,

are a primary, proven source of combat pilot learning. This structured process provides the opportunity for warfighters to review, evaluate, and learn from every moment of their mission execution so that they can apply these lessons and improve their effectiveness on the next sortie. CCA must become part of this debriefing process to develop critical lessons learned that will improve their future performance and operational effectiveness as team members.

Recommendations for the Air Force:

- Involve warfighters in developing CCA explainable machine learning user interfaces.
- Develop interactive mission planning, mission rehearsal, and debriefing tools to support continual learning and mastery of CCA performance and teaming operations.

Warfighters Must Be Able to Depend on CCA Autonomy

How do I know I can rely on my CCA teammates? Warfighters must have ways to assess the real-time performance, accuracy, and integrity of their teamed CCA. To operate effectively as a team, warfighters must be able to anticipate CCA behavior and trust that it will be consistent. Specifically, they must have confidence that their teammates will maneuver safely and effectively, have an accurate and mutual understanding of the battlespace, share critical information, maintain the same tactical priorities, and defer to human control. Without this dependability, warfighters could distrust or place too much trust in CCA in ways that undermine missions. For example, if humans do not trust CCA, they may suboptimize their teammates' performance or even refuse to use them in combat operations. Distrust may also lead warfighters to micromanage CCA, overloading warfighters with unnecessary tasks and negating the force-multiplying potential of CCA autonomous features. Alternately, if humans place *too much* trust in CCA autonomy, they may blindly accept divergent CCA behavior

CCA Dependability:

The probability that a CCA teammate will safely, consistently, and successfully maneuver and execute its assigned tasks and contracts in accordance with its mission role.

that undermines mission performance. CCA must be dependable and consistently behave in ways that their humans expect and need if they are to fully realize the potential of teaming. This will require the Air Force to develop processes to ensure the integrity of the software and flight safety and enable warfighters to assess and manage the real-time behavior of their CCA.

Develop Processes to Assure Algorithm Integrity and Data Security

Establishing trust in the levels of autonomy and machine learning in CCA will require giving warfighters the means to continuously monitor the health of the CCA agent and the veracity of its sensor data and other inputs. Warfighters must also trust in the integrity of their CCA agent's software and know that they have not been corrupted or maliciously hacked by an adversary. This will require processes to detect and reject malign attempts to attack, degrade, or control CCA. Given the evolutionary nature of AI/ML, developing and sustaining this degree of assurance and security must be part of everyday CCA operations. It cannot stop with CCA development. The nature of machine learning programs is to change and adapt with every data input and run repetition. These data-driven adaptations may yield improved mission performance, but changes in CCA behavior that are not transparent and understood may also obscure corrupted data or malicious attacks.

Like software programs that protect against malware in standard computers, capabilities must be built into CCA to examine data and other inputs to filter out the bad. These filters must be able to identify when erroneous data is simply the result of innocuous environmental elements or when it is part of an adversary's deliberate efforts to degrade the CCA agent, which should then be recorded and reported in real-time to the warfighter. This means CCA should have software that observes and oversees agent performance, monitors and measures their autonomy health during a mission, manages issues, and updates their status to their human teammate. Engineers and operators should collaborate to develop this "executive function" software to determine relevant

indicators and how best to report divergences or malfunctions to warfighters. Depending on the severity of the issue, problems might be recorded and reported as a fault to address post-flight, just as an avionics technician downloads the performance of aircraft systems today. Likewise, problems could be displayed to the warfighter as a master caution or warning indication that might affect operations immediately, like an engine fire or low fuel light. The malfunction might even require the executive function to override the CCA agent, effectively quarantining the CCA from continuing to perform its mission duties, sharing information, or even returning it to base. The warfighter may be able to remediate some issues through checklist actions, or the system might have a design that allows the CCA to continue operating at a diminished or degraded level.

CCA Performance Must Ensure Flight Safety

Humans must be able to trust that CCA will not fly into them, other aircraft, or the ground. Moreover, CCA teammates must not endanger friendly forces during missions, and they should minimize harm to non-combatants and civilians. While these requirements may seem obvious, developing software with the necessary attributes will require robust simulation and actual flights that incrementally test and then adjust their performance in increasingly difficult situations. For instance, DARPA's Air Combat Evolution (ACE) program demonstrated the ability of a CCA agent to maneuver safely and dynamically in limited dogfighting simulation scenarios, but many iterative cycles of test flights and development are needed to give CCA agents the ability to operate with many aircraft in the real world. DARPA is continuing to develop flight safety autonomy in ACE's second phase, and this program and others like it should be aggressively pursued. To further these developments, the Air Force should establish bases and ranges for CCA live-fly operations.⁶⁶

CCA Must Share the Same Battlespace Awareness as their Humans

For humans and CCA to effectively synchronize their efforts as a team and as part of a larger mission package, they must share the same understanding of the battlespace. This requires each element of a team to continuously update each other to improve the whole team's situational awareness. Maneuvering, coordinated action, tactical priorities, targeting, and other decisions and behaviors are all contextual—if a CCA agent does not have the same battlespace picture, it will not behave in the ways that humans need or expect. The need for a shared battlespace awareness is further complicated by the limitations of autonomy. When AI/ML algorithms are presented with environments that do not fit into previous training experiences, their behavior may be unpredictable or even dangerous. Divergent CCA behavior may counter human actions in the battlespace, confuse or complicate other elements of the mission package, or even fail to act at all.

Humans also must be able to identify, evaluate, and adjudicate differences between their battlespace awareness and that of their teammates. This does not mean that humans will always have the most accurate information, or that their sight picture should automatically override that of their CCA. Instead, aircrew need the option to peel back the layers of information from their sensors, those of their CCA, and other offboard sensor inputs to evaluate the quality and source of the data. Today's fifth-generation F-22 and F-35 pilots already experience this real-time presentation of data, which helps them share tactical awareness across aircraft in their flight. While the need to deconstruct the fused battlespace picture presented to them is uncommon, there are instances where fifth-

generation pilots must examine the specific data inputs and de-select those that they believe are misleading or lack quality. This ability is crucial to warfighter battlespace awareness and decision-making.

Human teammates also need to monitor and arbitrate their collective battlespace awareness to identify situations where their CCA are challenged by uncertainties and ambiguities. CCA logic may not be able to execute certain actions when they lack certainty in their data or tactical picture or when they confront novel scenarios. The Air Force's "AI Accelerator," developed in partnership with the Massachusetts Institute of Technology, highlights this machine learning limitation:

Many existing ML algorithms often fail catastrophically, however, when data inputs or task objectives change from those encountered during algorithm training. This lack of reliability combined with the opaque nature of modern ML techniques makes it impossible to deploy machine learning systems confidently in mission-critical environments.⁶⁷

Humans must use their applied understanding of how their CCA agent will respond to battlespace stimuli and other inputs so they may anticipate, preempt, and manage CCA behavior in unanticipated or untrained scenarios. This is critical to flight safety, the integrity of teamed operations, and mission success.

Recommendations for the Air Force:

- Develop processes for warfighters to assess the real-time integrity, performance, and accuracy of CCA operations.
- Ensure these processes provide warfighters with feedback on CCA algorithm integrity and data security.
- Ensure CCA performance accounts for flight safety and bases itself on the same battlespace awareness as teamed humans. Human teammates should also be able to monitor and assess this collective battlespace awareness to identify situations where actions are needed to compensate when CCA encounter situations they are not trained for.

Warfighters Must Have Assured Control Over CCA in Highly Dynamic Operations

How do I know that my CCA teammates will do what I tell them to, or do what I need them to do? Human operators must have assured control of their teammates to synchronize or redirect CCA behavior in changing, surprising, or uncertain circumstances. Control in a human-CCA teaming context refers to the human command authority over an autonomous teammate, like how a fighter flight lead would command a four-ship flight, or a mission commander would direct the execution of a mission package consisting of multiple aircraft. It does not mean performing functions such as directly controlling CCA flight surfaces, engine settings, or sensor management of current remotely piloted operations. Without this higher-level human authority, CCA actions in the battlespace may become, at best, disjointed and disconnected from their humans and the mission package.

Assured CCA Control:

The confidence that CCA will respond appropriately to human command and intent in novel scenarios or even when connectivity is contested.

In worst-case scenarios, CCA reacting to uncertain circumstances could behave in unpredictable ways that risk mission success. Furthermore, humans must retain resilient and reliable control of CCA teammates in high-stress operational environments where adversaries are attacking information networks to deny or collapse command and control to U.S. forces.

Understanding the Difference Between Directive and Descriptive Control Over CCA

When the level of CCA control is not automatically mandated by a procedure or normalized by standards, human teammates will typically need to choose between using directive or descriptive control actions. Directive control is often used in low-trust teaming relationships to “fix” CCA teammate errors or continue operations when a teammate is determined to be not fully competent. Fighter flight leads often use directive control with new wingmen because they lack the experience and skill to accurately perceive the battlespace, make good teaming decisions, and then maneuver effectively. However, directive control is burdensome for a flight lead because they must closely monitor and assess their wingman’s actions, project themselves into the wingman’s cockpit and decision-making process, and essentially fly the mission for them.

At the other end of the control scale, humans use descriptive control when they have high trust in their teammates or are task saturated. In a high-trust teaming scenario, humans use descriptive control because they believe the teammate shares their battlespace awareness and will act appropriately. A benefit of descriptive control is that it provides the greatest independence in action and could enable innovative CCA behaviors while decreasing human workloads. This allows humans to shed workload when they are over-tasked during a mission. When using higher levels of descriptive control, humans articulate the objective with little additional guidance. This level can enable CCA to make unorthodox tradeoffs, maneuver in surprising ways, or choose novel solutions to achieve the stated effect. In one set of simulations conducted by a DOD industry partner, a swarm of autonomous aircraft chose to form a large grouping during target ingress, accepting losses on the outside of the formation to ensure that those on the interior would make it to the target.⁶⁸

Descriptive CCA control is not without its hazards. Autonomous software can misinterpret or fail to recognize new and different stimuli or contexts, which can result in adverse CCA behaviors. As in the AI Accelerator example, MIT and Air Force collaborators identified the inability of the many ML models to adapt to changing environments as a difficult problem for autonomy employment. Yet these unanticipated or confusing scenarios in which CCA may need directive control are also exactly when humans most need to employ descriptive control paradigms to reduce their own burden.

Teammates Should Have the Ability to Flexibly Shift Between Different Control Paradigms over the Course of a Mission

To facilitate effective teaming operations, humans must be able to dynamically adjust their level of CCA control based on real-time battlespace demands. This means humans should be able to fluidly shift between directive and descriptive control as needed over the course of a mission. This adaptability is important to optimize human workloads, exploit the unique attributes of CCA, and respond to changing battlespace conditions.

Control paradigms can range from very specific and directive to outcome-oriented and descriptive. In this way, control can be thought of as a scale that human commanders move across as situations dictate. For example, a fighter flight lead would use tight, directive control to tell his inexperienced human wingman to “abort,” or perform a maximum-G, 180-degree slicing turn in afterburner in the event the wingman flew too far into an adversary’s missile-launch range. Another example of this directive control would be a wingman directing the flight lead to “break right, flare” if they saw an adversary aircraft maneuvering into an offensive position. In this situation, the wingman is directing a maximum-G, idle turn to the right, and deploying flares as a defensive response to spoil any potential adversary shot. On the other end of the spectrum, a flight lead might “clear off” a wingman to investigate an unknown potential pop-up threat on their own because the flight lead is committed to another engagement. In this case, the flight lead is communicating their intent and consent that the wingman will independently execute within the briefed game plan, in accordance with the rules of engagement, and in support of the mission objectives. Human-human teams routinely move across these paradigms of control during mission execution.

Air Force and defense industry technologists must work with warfighters to define the levels of CCA control they will need in combat operations, grappling with the tension between control paradigms, human workload, and CCA performance. Humans should be able to seamlessly move back and forth along the directive-descriptive scale of control, as should CCA. As in other CCA developmental efforts, warfighters must be an integral part of decomposing and defining the attributes of these controls.

CCA Must Proactively and Responsively Communicate with Humans to Assure Control

Humans often provide a verbal acknowledgment to their flight leads or other mission authorities to indicate that they have received a command and provide affirmation that they will comply. But assured control does not mean that CCA simply acknowledge and blindly execute human directives. True teaming involves a proactive and

responsive communication cycle. For example, an experienced wingman might have information that changes a tactic or game plan, and they may suggest a course of action to the flight lead or even direct the flight to act—which the lead can always override. Alternately, a wingman might respond to a flight lead directive with a “negative” or “unable,” rejecting the direction and immediately following with a brief explanation for why. Communication that assures control includes exchanges that improve the teams’ collective battlespace awareness, suggest courses of action, close information requests, request permissions, and acknowledge commands, among others. Warfighters must work with technologists regarding the kinds of information they need from their teammates to assure human control and the best means to display and convey those exchanges.

The Air Force Must Prioritize Resilient Connectivity as a Technical Priority for Teaming Efforts and Develop “Comm-Out” Contingency Plans for CCA

CCA control teaming operations are heavily reliant on networks that connect all aircraft in a team. Without the ability to communicate, humans will struggle to control their autonomous teammates. This problem is little different than what modern human teams face. Connectivity is becoming the foundation of U.S. Air Force operations as it moves toward developing disaggregated capabilities, detached formations, systems that provide beyond-visual-range support to each other in contested areas, kill webs, and other networked functionalities. This means the Air Force must continue to prioritize developing resilient communications to integrate operations, including human-CCA teaming missions.

Effective control can become especially challenging when combat situations are unexpected or confusing, as this can easily task-saturate humans and confound their CCA. To facilitate assured control, CCA must provide both proactive communication and responsive feedback to their human. CCA must continue to effectively team with their humans in ways that are aligned with mission objectives, even in worst-case contingencies where communications or datalinks are denied or break down. Human teams have successfully operated with these kinds of communications-out contingency plans, or “contracts.” These include using visual signals, like wing rocks, to communicate a rejoin or another cue to switch to an alternate, pre-briefed game plan that uses precision timing to synchronize actions. In this latter scenario, the mission objective, established rules of engagement, special instructions, and the human briefing create the bounds of acceptable behavior and provide for a degree of control. In this contingency case, it will be important for humans to understand the limits of CCA autonomy and deliberately craft a realistic and acceptable comm-out contingency plan as part of community standards and mission planning.

Recommendations for the Air Force:

- Develop teammates that can flexibly and appropriately shift between different control paradigms over the course of a mission.
- Ensure that CCA proactively and responsively communicate with humans to assure control.
- Prioritize resilient connectivity as a technical priority for teaming efforts and develop “comm-out” contracts for CCA.

Human Workloads Must Be Manageable

Will operating with my CCA teammates task-saturate me and make me less mission effective? Humans must be able to communicate, collaborate, and control their CCA with the least amount of friction inside their own cockpits, even as their own task load increases in a complex battlespace operation. Warfighters will not find CCA useful if managing them detracts from their ability to perform primary mission duties or jeopardizes mission success. These concerns extend beyond CCA flight control mechanics to communication, coordination, and other mission integration tasks.

The development and integration of air-to-air missiles offer useful insight here. When the AIM-9 Sidewinder was first in development, the engineers intended to use a voltmeter to indicate to the pilot that the missile had a good “lock” on an airborne target. U.S. test pilot Glenn Tierney objected: “You mean the pilot . . . has to take his eyes off his target and look at a gauge to see if the missile . . . sees the target? That’s unacceptable.”⁶⁹ Technologists then figured out how to use an audible tone—the iconic growl and tone—to cue a pilot that an AIM-9 missile seeker had enough infra-red energy to lock on and track a target. Today, pilots use a variety of sensors, including their helmet, to cue AIM-9s, check the tone for lock, verify launch performance parameters in their heads-up display or helmet, and then launch the missile—all without taking their hands off their throttle and stick or “looking down” from the engagement.

Technologists will similarly need to work through every CCA teaming interaction with warfighters to ensure their employment is as intuitive and frictionless as possible. This will help human aircrew to reserve their finite cognition “budget” for higher-level tasks like interpreting the battlespace, making decisions, and executing tactics. The full potential of teaming will not be realized if warfighters must continually shift their attention from performing their primary duties to thinking about the mechanics of CCA operations. User command and

Crew Workload:

The measure of how much cognitive load and functional tasking autonomous teammates impose on human flight leads and mission commanders.

control interfaces—the logic, displays, and mechanics warfighters use to interact with their CCA—must be deliberately integrated across the mission lifecycle of the CCA in ways that honor human factors, established human habit patterns, *and* weapons system functionality. This will also require designers to consider and program these interfaces into the warfighter’s weapon system.

Technologists Must Collaborate with Warfighters to Develop Intuitive User Interfaces

Technologists will need to work with warfighters to decompose teaming operations and then leverage existing symbology, “switchology,” and habit patterns to create intuitive user interfaces. Teaming interactions must be thought through the entire mission execution cycle, from engine start to engine shutdown. Engineers must decompose teaming interactions across the span of missions into collaboration tasks with warfighters since only warfighters can provide the requisite fidelity on mission workflows. Elements of these teaming dynamics include how CCA will communicate with their human, how the human will direct or control CCA, the kinds of information they exchange, and how manned aircraft and CCA must maneuver.

Technologists then have the hard work of thinking through how to best present information to warfighters so they can effectively command their CCA. It is important that CCA user interfaces avoid creating friction in the cockpit or inducing human errors by contradicting established cockpit control switch functions. Humans must have an intuitive interface with their teammates—displays, controls, and feedback that can be easily processed contribute to situational awareness rather than distract. Established manned aircraft standards, norms, and processes already exist that can serve as models for this. For example, pressing forward on a fighter aircraft’s target management switch commands a radar lock on a target in one mode and a datalink “lock” or “hook” in another mode. Similar switch functions and equipment manipulations that are familiar to aircrew would increase the effectiveness of CCA user interfaces. As another example, flight leads routinely direct their wingmen through datalink commands, and these very same habit patterns can be used for CCA and need not be reinvented. This is like developing new smartphone operating systems and controls by building off earlier versions with functions and manipulations that users are already familiar with. Exploiting established habit patterns, switchology, and weapons system functionality can also reduce the time and effort needed to create new interfaces between CCA and manned aircraft.

CCA User Interfaces Must Be Fully Integrated into a Warfighter’s Weapon System Operational Flight Program (OFP)

While it might seem easy and pragmatic to simply strap a generic tablet into a cockpit to interface with CCA, it should not be the preferred solution because it would require users to pull their attention away from other mission displays. There’s a reason why combat aircraft mission information and weapons control migrated over time from cockpit instrument panels to head-up displays and then to helmet-mounted displays like those used by F-35 pilots. This dramatically improved human pilots’ ability to control their aircraft and employ their sensors and weapons. This decreased workload supported mission success because these integrated displays and controls did not require them to divert attention from engaging in combat. Instead, CCA user interfaces should follow the model of missile information and weapons control and be fully integrated into a warfighter’s operational flight program (OFP). The OFP is the program that runs, processes, and controls all sensor inputs, avionics, displays, and weapons on combat aircraft. Integrating CCA user interfaces in OFPs will enable machine-to-machine data exchange, increase shared battlespace awareness, and foster the most intuitive human understanding and interaction with CCA teammates.

Developing and integrating an intuitive CCA user interface into the warfighter’s OFP does not need to be complicated, but it will require the active participation and support of weapons system communities and program managers to facilitate timely integration across the combat air forces. If they don’t, then CCA may not have a partner to team with. Furthermore, just as weapons like the AIM-9 or AIM-120 missiles families have standardized symbology and can be integrated into many different types of aircraft, CCA will need standards that can cross communities and be integrated into many different weapons system OFPs, including those of airborne stations or ground stations. This is especially important to enable CCA to team with different aircraft and weapons systems.

Recommendations for the Air Force:

- Foster collaboration between technologists and warfighters to develop intuitive human interfaces with CCA.
- Fully integrate CCA command and control interfaces into the warfighter’s weapon system operational flight program.

Conclusion and Recommendations

Today, the Air Force is too old, too small, and does not have the right force design to prevail in a large-scale, high-end conflict with China. CCA can play a key role in transforming the Air Force's force design into one that can win. The speed and miniaturization of processing, coupled with advanced software programming and machine learning, make it possible for CCA to do far more than “dumb, dangerous, or dirty” missions, the purview of older, less sophisticated unmanned systems. Operating CCA at scale could provide the mass and operational tempo needed to create an attrition-tolerant and resilient force in an Indo-Pacific peer conflict. CCA autonomy can also help the Air Force side-step pilot production timelines to field “experienced” agents to replace some aircraft attrited in combat, giving it a strategic edge in protracted conflicts. Moreover, the form and function of CCA can present a disaggregated and more complex force to the adversary, extending their decision cycles and confounding their defensive operations. These are ways CCA could become true force multipliers for the Air Force—if it gets their development right.

The key to fielding effective CCA will be developing effective human-CCA teaming features. Technologists have focused on proving the viability of autonomous aircraft by decomposing missions into discrete tasks and demonstrating the ability of autonomous aircraft to execute those tasks. In this model, humans have been treated as the occasional data input, just like other sensors or datalinks, and not as true partners. Combat-effective teaming is far more complex and densely interactive. Most importantly, teaming must also honor human performance factors and limitations.

For CCA to be successful, they must team with humans, and that means *integrating human factors into teaming algorithms and software*. Fortunately, existing human formations can serve as established, high-performing models for technologists to emulate as they develop CCA teaming features. Human-piloted aircraft formations, whether a two-ship of fighters or an entire mission package, have processes, procedures, interactions, and other teaming and control structures that have proven effective in extremely demanding operational environments. Decades of real-world experience have molded these teaming norms and standards to human behaviors. Modeling CCA teaming architectures based on these proven operational constructs will create trust in their operations and help warfighters achieve desired mission outcomes in stressing scenarios.

Building CCA that will be effective teammates will also require Air Force leaders, policymakers, and technologists to understand how to exploit the relative strengths of humans and CCA to create effective teams; ensure that warfighters understand CCA autonomy and performance envelopes; create safe and dependable CCA that humans can trust; assure human control of CCA; and ensure that human workloads remain manageable when operating as part of a human-CCA team. These teaming considerations must be prioritized and developed with

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other CCA autonomy for one fundamental reason: they must be programmed from the beginning—they cannot be patched in after CCA agent development. These teaming factors will interact with and impact mission task algorithms and other programming on a structural level. Teaming, done right, does not exist in isolation from other mission tasks. This demands greater emphasis in the CCA developmental process.

These recommendations summarize actions that Air Force leaders, policymakers, and technologists should take to create effective human-CCA teams:

1. **Optimize the composition of human-CCA teams.** Humans and CCA must be seen as more than the sum of their sensors, weapons, and other physical capabilities. Engineers and program planners should design CCA to perform as part of human-CCA teams that complement each other and rely on teaming dynamics and behaviors that maximize their combined operational potential. This will require the Air Force to:
 - Identify the key relative strengths and weaknesses of humans and CCA to build the right human-CCA teams.
 - Develop concepts of employment and tactics, techniques, and procedures to exploit these team strengths and mitigate their shortfalls.
 - Program teaming dynamics into CCA, modeled on proven human-human combat team interactions.
 - Build mastery of CCA teaming through continual test and training.
2. **Include operators in CCA development and provide them with the tools they will need to understand how CCA will perform in the battlespace.** Just as pilots must understand the flight handling qualities and performance envelopes of their aircraft to maximize their employment, warfighters in CCA teams must understand the CCA autonomous agent to operate effectively as a team. Moreover, both humans and CCA must be able to hone their partnership and evolve the quality of their teaming operations. This will require the Air Force to:
 - Involve warfighters in developing CCA explainable machine learning user interfaces.
 - Develop interactive mission planning, mission rehearsal, and debriefing tools to support continual learning and mastery of CCA performance and teaming operations.
3. **Ensure warfighters can depend on CCA autonomy.** To operate effectively as a team, warfighters must be able to trust their CCA. Warfighters require confidence in the integrity of their CCA's agent and a knowing that it will consistently behave as they expect and need. This will require the Air Force to:
 - Develop processes for warfighters to assess the real-time integrity, performance, and accuracy of CCA operations.
 - Ensure these processes provide warfighters with feedback on CCA algorithm integrity and data security.
 - Ensure CCA performance accounts for flight safety and is based on the same battlespace awareness as teamed humans. Human teammates should be able to monitor and assess this collective battlespace awareness to identify situations where actions are needed to compensate when CCA encounter situations they are not trained for.

4. **Ensure warfighters can maintain assured control over CCA in highly dynamic operations.** Human operators must have command authority over their teammates to synchronize or redirect CCA behavior in changing, surprising, or uncertain operational circumstances. This will require the Air Force to:
 - Develop teammates that can flexibly and appropriately shift between different control paradigms over the course of a mission.
 - Ensure that CCA proactively and responsively communicate with humans to assure control.
 - Prioritize resilient connectivity as a technical priority for teaming efforts and develop “comm-out” contracts for CCA.

5. **Ensure teaming workloads are manageable for humans.** Humans must be able to communicate, collaborate, and control their CCA with the least amount of friction inside their own cockpits, even as their own task load increases in complex battlespace operations. Not only must teaming be programmed into the CCA from the beginning, but *how the human will team* with the CCA must also be considered and programmed into the human’s weapon system. This will require the Air Force to:
 - Foster collaboration between technologists and warfighters to develop intuitive human interfaces with CCA.
 - Fully integrate CCA command and control interfaces into the warfighter’s weapon system operational flight program.

Autonomous aircraft will not replace humans in the battlespace. Humans will continue to be the essential qualitative advantage in highly contested peer conflicts because of their cognitive flexibility, adaptation, intuition, and other ineffable human traits. Yet collaborative combat aircraft have the potential to do far more than simply augment human missions. CCA can become true force multipliers for the Air Force in ways that far exceed the value of quantity—*if* their teaming operational concepts, software, interfaces, and other capabilities are developed correctly. To exploit the full potential of CCA, Air Force leaders, policymakers, and technologists must focus on creating effective human-CCA *teams*, and this demands a greater emphasis on building human-CCA teaming dynamics.

One foundational truth stands: human warfighters are the keystone to this transformation. Only human warfighters can provide their exclusive insight into the demands of teaming operations in uncertain, highly dynamic combat environments. They *must* be involved in the early stages of the Air Force’s CCA development to shape how these autonomous aircraft will operate with humans in the battlespace. As teaming concepts with CCA become more normalized and proliferated in the Air Force, CCA battle management may become a primary responsibility for humans in combat. In the meantime, however, Air Force leaders and technologists must prioritize human teaming dynamics as they aggressively pursue the development of CCA. Failing to do so risks more than sub-optimizing CCA designs; it risks losing the next war. ✪

Endnotes

- 1 The Air Force Scientific Advisory Board described CCA as “combat aircraft employing a distributed, mission-tailorable mix of sensors, weapons, and other mission equipment... To realize the CCA concept with acceptable pilot workload, the uncrewed aircraft will need to be semi-autonomous, taking high level direction from the pilot and then autonomously implementing this direction. Recent advances in artificial intelligence (AI) and machine learning are believed to enable this approach.” Department of the Air Force Scientific Advisory Board, “[Collaborative Combat Aircraft for Next Generation Air Dominance](#),” 2022, p. 1.
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- 3 Abraham Mahshie, “[Kendall: Air Force Has an ‘Affordability Problem’ As It Tries to Meet Capability Gap](#),” *Air Force Magazine*, June 1, 2022.
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This can be explored by creating simulation space for CCA to “improvise” behaviors based on data collected from the real world, then “freezing” CCA autonomy during physical employment.

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