Collaborative Combat Aircraft: The Effectiveness and Optimization for Military Operations

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This study examines the design and optimization of Collaborative Combat Aircraft (CCAs), new artificial intelligence wingmen being developed under the Next Generation Air Dominance program, within the context of modern military operations, emphasizing their role in enhancing air superiority. Multiple unmanned drone designs were analyzed under certain design characteristics, performance metrics, and technological capabilities and then compared to each other to find the most important qualities needed in a CCA. Key findings show that modularity and payload capacity are critical for mission adaptability, while speed and maneuverability must be optimized based on operational threats. Developers are constructing artificial intelligence systems with the goal of efficiency and enabling real-time decision-making but need to keep ethical consequences in consideration. Human-machine teaming is essential for operational success, though trust in autonomous systems remains a challenge. Wargame simulations and network theory demonstrate that combining expendable, lower-cost CCAs with more advanced, survivable models enhances mission adaptability and operational resilience. These findings show that expendable CCAs protect manned aircraft in high-risk environments, while advanced models with stealth and superior communication systems are essential for complex, high-stakes missions, ensuring sustained air superiority across various combat scenarios. This research concludes that a diversified fleet of CCAs, tailored to specific mission profiles, maximizes operational flexibility, cost efficiency, and survivability, ensuring the United States Air Force's tactical advantage in future combat scenarios.

Keywords: CCA, UAV, MAV, AI, drone, machine-learning, Air Force, NGAD, collaborative combat

Introduction

Collaborative Combat Aircraft (CCAs) represent a significant advancement in military aviation, integrating artificial intelligence (AI) to enhance the capabilities of modern combat. Merging machine-learning with current drone technology, these aircraft are planned to function as wingmen for humans during military operations. CCAs are a critical component of the Next Generation Air Dominance (NGAD) plan, which is the United States Air Force's (USAF) strategy to maintain air superiority through advanced technological innovation. NGAD and the development of CCAs are driven by the need to maintain air superiority and respond to the rapid advancements in military technology by other nations, particularly China[1]. The NGAD plan aims to develop a family of systems that include manned and unmanned aircraft, leveraging cutting-edge technologies to create a highly adaptable and resilient aerial combat force. The USAF recently chose General Atomics Aeronautical Systems and Anduril Industries to develop CCAs, encouraging healthy competition to find strong designs for CCAs. Anduril Industries, a relatively newer company, and General Atomics Aeronautical Systems, a well-known veteran in the field, will develop and test production-representative CCAs under Increment 1, the first phase in the production plan, with a winner to be chosen in 2026. Despite contenders for Increment 1 already being selected, USAF encourages other companies to also develop CCAs with the potential to be selected for Increment 2[2]. This approach allows for rapid technological advancement and continuous improvement through ongoing competition and innovation among defense contractors. The push for CCA technology has led to various research programs and initiatives by the USAF and other military organizations.

Programs such as Skyborg, Variable In-flight Simulator Aircraft (VISTA), and the Air Combat Evolution (ACE) are spearheading the development and testing of autonomous aerial systems that can operate alongside crewed aircraft. Launched in 2019, Skyborg is a government program that aims to develop an AI-driven reference architecture capable of controlling various unmanned aerial vehicles (UAVs). The goal is to create a modular and scalable architecture that can be integrated into different aircraft to enhance their operational capabilities. Skyborg focuses on enabling UAVs to conduct complex missions independently or in conjunction with human pilots, thereby increasing the flexibility and effectiveness of the USAF's combat operations[3]. VISTA is a modified F-16 fighter jet used by the USAF and the Defense Advanced Research Projects Agency (DARPA) to test and validate new technologies, including autonomous flight systems. In recent tests, VISTA has demonstrated the ability to conduct dogfights using AI, showcasing the potential of autonomous systems to handle complex and dynamic combat scenarios. The ACE program, led by DARPA, focuses on developing and refining AI technologies for aerial combat. By using simulations and live flight tests, ACE aims to build trust in autonomous systems and ensure they can perform effectively in various combat roles[4]. The program's ultimate goal is to integrate these AI capabilities into CCAs, enhancing their ability to operate alongside human pilots and other autonomous systems.

The importance of CCAs in modern warfare cannot be overstated. These unmanned systems are designed to perform a multitude of missions, from reconnaissance to direct combat, thereby reducing the risk to human pilots and increasing operational efficiency. The ability of CCAs to operate autonomously or semi-autonomously allows for greater flexibility and strategic advantage in various combat scenarios. The rapid advancements in military technology by nations such as China have highlighted the need for innovative solutions to maintain air superiority. Traditional manned aircraft, while highly capable, are limited by human endurance and the risks associated with putting pilots in harm's way. CCAs offer a solution by providing a force multiplier effect, enabling the USAF to project power more effectively and efficiently. They are relatively cost-effective when compared to manned aerial vehicles (MAVs) and can be rapidly deployed and adapted to different missions.

This research aims to address what key design characteristics, performance metrics, and technological capabilities define the optimal aircraft for collaborative combat operations. Additionally, how can these characteristics be integrated to enhance joint mission effectiveness, safety, and interoperability between allied forces? The purpose of this study is to identify and analyze the attributes that make CCAs effective in combat situations. By understanding key design characteristics and performance metrics, this research will contribute to the development of more efficient and capable CCA systems. This study's findings will be relevant to current and future combat operations, providing insights that can help maintain air superiority and improve collaborative efforts among allied forces. The integration of AI and advanced technologies into CCAs represents a pivotal shift in military aviation. By leveraging these advancements, the USAF aims to enhance its operational capabilities and maintain a strategic edge over potential adversaries. This research will provide a comprehensive analysis of the design and performance metrics that define optimal CCA systems, offering valuable insights for their future development and deployment.

What are CCAs? Why are they important?

CCAs are UAVs designed to operate autonomously or semi-autonomously alongside manned aircraft. They leverage AI to perform a variety of combat and support missions, effectively acting as force multipliers in aerial operations. By integrating machine-learning and advanced sensors, CCAs can carry out tasks that would traditionally require human pilots, reducing risk and enhancing operational efficiency.

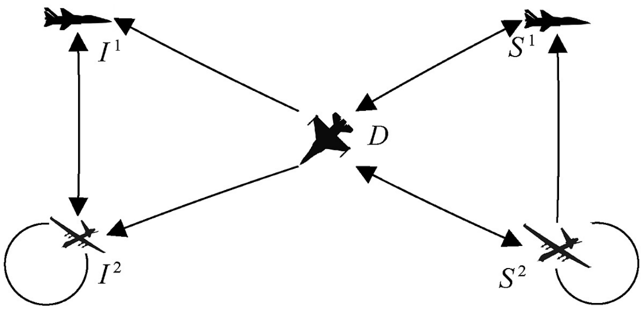


Fig. 1 A network topology illustrating the necessary conditions that need to be followed in collaborative combat. All aircraft are unmanned except for aircraft D, which is piloted by a human. The manned aircraft cannot be overloaded with processing data, therefore the only aircraft feeding information are S^1 and S^2. All nodes must have one connection to D to be properly controlled when there are unexpected problems[5].

CCAs are planned to perform multiple roles, from gathering information to direct combat in military operations. Initially, these aircraft will focus on carrying additional munitions and providing electronic warfare support. As their capabilities evolve, their roles will expand to include intelligence, surveillance, reconnaissance (ISR), and other mission types[6]. The strategic importance of CCAs lies in their ability to augment the capabilities of manned aircraft, enhancing the overall effectiveness of air combat operations. Traditional MAVs, while capable, face limitations due to human endurance and the risks of piloted missions. In addition, the processing of vast amounts of data can be time-consuming and, in fast-paced combat scenarios, be limited by a human's capabilities. CCAs offer a solution by providing persistent surveillance and response and the ability to take high-risk missions without putting a human life in danger. This is modeled in Fig. 1, where a network topology details the interactions between MAVs and UAVs to avoid overloading pilots. One of the key advantages of CCAs is their operational flexibility[5]. These aircraft can be rapidly reconfigured for different missions, allowing for a quick response to dynamic combat situations[7]. This adaptability is crucial for maintaining a tactical edge in modern warfare, where the ability to quickly switch between different roles and missions is important. As part of the NGAD initiative, the USAF plans to produce and deploy 1,000 to 2,000 CCAs by the mid-2030s[8]. Their deployment ensures the USAF remains at the forefront of military innovation and can effectively respond to evolving global security challenges.

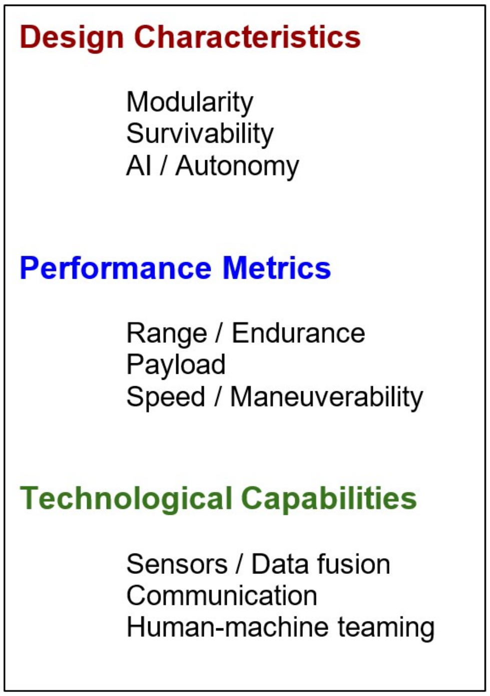
Additionally, CCAs are planned to be cost-effective alternatives to MAVs. Developing and maintaining a fleet of UAVs is less expensive than manned counterparts as they do not need to account for a human operator and therefore no safety technology is needed. This cost efficiency will enable the USAF to field a larger number of aircraft, increasing its operational reach and flexibility; however, as development of this technology continues and more resources are found to be necessary, contractors will prove to be the deciding factor of the price range of these aircraft. The integration of AI and advanced systems into CCAs represents a significant technological advancement in the military. These technologies allow CCAs to make real-time decisions, adapt to changing combat scenarios, and operate effectively in contested environments[9]. The ability to process vast amounts of data and act on it autonomously enhances the decision-making capabilities of CCAs, making them invaluable assets in modern warfare.

Material & Methods

The analysis of the literature focuses on understanding the key design characteristics, performance metrics, and technological capabilities that define an optimal CCA. The goal is to synthesize existing knowledge to identify what makes a CCA efficient and to determine the criteria by which the "best" CCA designs can be judged. Sources will be selected based on their relevance to the specific aspects of CCAs being analyzed. Due to this being very recent technology as of 2024, all articles will be relevant. A comparison will be conducted to highlight the strengths and weaknesses of various CCA designs and how these can be balanced. Below are the key aspects that will facilitate this comparison:

1. **Design Characteristics:**
    - Modularity: Allows CCAs to be reconfigured for different missions by swapping payloads, sensors, and weapon systems. Enhances operational utility, extends service life, and facilitates easier maintenance and upgrades.
    - Survivability: Involves the use of low-observable technologies to reduce radar cross-section (RCS) and avoid detection by adversaries. Backups for these systems ensure continued operation even if some components fail. Maneuverability contributes to a higher survivability in combat.
    - AI Integration: Enables autonomous decision-making through machine learning, allowing CCAs to perform complex tasks without human intervention. Reduces cognitive load on human operators and enhances their role as effective wingmen.
2. **Performance Metrics:**
    - Endurance and Range: High endurance allows CCAs to stay airborne for extended periods, crucial for intelligence, surveillance, and reconnaissance (ISR) missions. Range determines the distance CCAs can travel from their launch point, essential for long-distance missions.
    - Payload Capacity: Defines the amount and type of equipment a CCA can carry, influencing mission versatility. A flexible payload capacity supports different munitions, sensors, and electronic warfare systems, but must be balanced with speed and range to maintain optimal performance.
    - Speed and Maneuverability: High speed is necessary for reaching targets quickly and evading threats, while maneuverability allows for complex flight patterns and evasive maneuvers in contested airspace. The design must balance these with other factors like payload capacity.
3. **Technological Capabilities:**
    - Sensors: Include radar, infrared, and cameras to gather data and provide situational awareness. Data fusion integrates information from multiple sources, enhancing adaptability and operational decision-making.
    - Communication Links: Facilitate real-time data sharing with other aircraft, command centers, and ground units. Essential for human-machine teaming and maintaining network integrity in contested environments through encryption and anti-jamming technologies.
    - Human-Machine Teaming: Involves designing intuitive control systems that allow human pilots to direct CCAs easily, supporting complex mission planning and execution. Maintains CCA autonomy for independent decision-making if communication is lost, ensuring mission success.

Modularity will be rated based on the flexibility of the aircraft to be reconfigured for various missions, mainly relying on the payload size, and how modularity affects overall mission readiness and operational efficiency. Survivability will be measured based on the drone's RCS, which can be estimated from its size and material properties. AI integration is evaluated by how well the system can compile information received by the sensors and make decisions. The analysis of range and endurance will focus on how long these aircraft can remain operational and the distances they can cover, emphasizing the ability to perform long-range missions. Payload capacity, affecting the versatility and other performance metrics of the CCA, will also be a key focus. Speed and maneuverability will be assessed



Design Characteristics

Modularity
Survivability
AI / Autonomy

Performance Metrics

Range / Endurance
Payload
Speed / Maneuverability

Technological Capabilities

Sensors / Data fusion
Communication
Human-machine teaming

Table 1: A list of the evaluated aspects for the optimization of CCAs. The design characteristics, performance metrics, and technological capabilities each have three points for analysis

based on propulsion systems and the ability to balance these with other aspects like survivability and payload. Sensors and data fusion will be evaluated in relation to payload and AI integration. Efficiency in communication will be judged by the ability to maintain links in contested environments. The Skyborg systems will be analyzed for their role in enabling effective human-machine teaming.

Efficiency in CCAs will be defined by how well these aircraft meet modern combat requirements, including versatility, survivability, and mission effectiveness. The optimal designs will balance these aspects while integrating AI, sensors, and other technologies effectively. The analysis will compare different designs to identify the most balanced solutions and highlight gaps where current technologies or designs may need improvement. This could include enhanced AI capabilities, better modular integration, or more robust communication networks. By identifying these gaps, the study will suggest areas for future research and development to improve the effectiveness and versatility of CCAs.

Results

Recent studies on AI-powered drones in military scenarios will be analyzed to provide a detailed comparison of various drone technologies and their implications for the design of the optimal CCA. The strengths of each drone system will be highlighted and then compared to others under each key aspect.

The drone family consisting of Samad-1, Samad-2, and Samad-3 demonstrates significant advancements in delivering long-range, precision strikes. The most recent design was estimated to have approximately 1900km of range in optimal flying conditions. Samad-3 had a maximum take-off mass of about 100kg with 18 of that being in the payload[10]. This drone design has a significant amount of payload size and range capabilities, making it suitable for long-range attacks. However, the Samad series also has limitations. Their large size means they have relatively low agility and are more susceptible to detection by advanced air systems. The lack of advanced maneuverability reduces their effectiveness in heavily defended airspaces. This suggests that while Samad drones excel in long-range, high-impact missions, they aren't as ideal for missions requiring stealth or rapid response.

Members at the Mitchell Institute for Aerospace Studies highlight the importance of balancing attributes such as size, cost, survivability, and mission systems in CCA design. The analysis indicates that a mix of drones with different capabilities could provide strategic advantages. They detail different levels of CCA drones, starting from $2-15 million for more expendable missions to greater than $40 million for non-attritable missions[10]. The lower-level drones would have less range, lower-cost sensors, and fewer munitions. As the price increases these also increase, along with their survivability becoming low observable (LO) or very low observable (VLO). However, the analysis revealed that their high price did not justify their use in most scenarios, as they approached the cost of MAVs like the F-35A. It is better to use the least costly aircraft in missions with a higher-threat environment to preserve resources if that aircraft is lost. Thus, the optimal CCA design should incorporate a diverse fleet that balances high-end capabilities with lower-priced, expendable options, ensuring operational flexibility.

Skyborg represents a significant advancement over the past five years in the integration of AI with autonomous flight capabilities, emphasizing modularity and adaptability. Designed to work alongside human pilots, Skyborg's framework can undertake a wide array of missions, including surveillance, air-to-air combat, and precision strikes. One of Skyborg's key advantages is its ability to combine sensor data, make decisions independently, and execute missions with minimal human input[11]. This adaptability is essential for maintaining operational effectiveness in contested environments where communication may be disrupted. Skyborg raises concerns about the reliability of AI in unpredictable situations and the ethical implications of autonomous combat. These challenges will need to be addressed through rigorous testing and the establishment of clear operational guidelines. Now, Skyborg is no longer an independent project and it instead merged with CCAs. Due to criticisms about Skyborg being a government program, defense companies

CCA-1: Counterair
- Survivability: VLO (Supersonic capable)
- Range: 2,000 nm
- Sensors: AESA, IRST
- Weapons: 2 x SiAW, 4 x AMRAAM
- Takeoff: Runway independent
- Landing: 5,000 ft

CCA-2: Counterair
- Survivability: VLO (Supersonic capable)
- Range: 3,000 nm
- Sensors: AESA, IRST
- Weapons: 2 x SiAW; 2 x JATM
- Takeoff: Runway independent
- Landing: 5,000 ft

- Notional CCA missions, capabilities, and categorization provided by warfighters and technological and defense industry experts during Mitchell Institute's 2022 wargame
- 2023 wargame players chose from these notional CCA designs

CCA-3: Counterair
- Survivability: VLO
- Range: 3,000 nm
- Sensors: AESA, IRST
- Weapons: 6 x AMRAAM
- Takeoff and landing: 5,000 ft

CCA-4: Counterair / SEAD
- Survivability: VLO
- Range: 3,000 nm
- Sensors: SAR, ATR
- Weapons: 6 x SiAW
- Takeoff and landing: 5,000 ft

CCA-6: Strike
- Survivability: No LO
- Range: 1,000 nm
- Sensor: None
- Weapons: 2 x LRASM
- Takeoff and landing: 5,000 ft

CCA-9: ISR, Communications
- Survivability: LO
- Range: 1,000 nm
- Sensor: SAR
- Weapons: None
- Takeoff & landing: Road, runway

CCA-10: Electronic Attack
- Survivability: VLO
- Range: 3,000 nm
- Sensor: EW pod
- Weapons: None
- Takeoff and landing: 5,000 ft

LO/VLO = Low/very low observable
SiAW = Stand-in Attack Weapon
JATM = Joint Advanced Tactical Missile
LRASM = Long Range Anti-Ship Missile
ATR = Automatic target recognition

CCA-5: Counterair
- Survivability: LO
- Range: Greater than 650 nm
- Sensors: Low-cost passive
- Weapons: 2 air-to-air weapons
- Air-launched, ground by rocket

CCA-7: Strike/ISR *(loitering)*
- Range: 1,000 nm rocket launched
- Sensor: Low-cost EO/IR
- Each CCA-7 deploys 20 small loitering PGMs with warheads

CCA-8: Strike/ISR *(loitering)*
- Range: 600 nm
- Survivability: VLO
- Sensor: Low-cost synthetic-aperture radar
- Air-launched, 500 lb. warhead

Fig. 2 Mitchell Institute details different production concepts for CCA to choose from when planning future combat scenarios. The cost is proportional to the CCA's capabilities, such as survivability, range, and offense[10].

have begun to develop their own efficient AI systems to sell to the military. Adaptive AI is a revolutionary technology in the military and allows aircraft to adjust to changing mission parameters in real time, enabling the USAF to have a basis for producing CCAs. However, ethics need to be taken into consideration when furthering its development to properly account for the consequences associated with using machine-learning in operations.

VISTA's experiments, particularly on AI-driven dogfighting and trust in autonomous combat scenarios, demonstrate the potential of systems in high-stakes aerial combat. The X-62A VISTA, a modified F-16, engaged in 21 test flights where it challenged a human-piloted F-16. These tests, conducted at speeds up to 1,200 mph and within 2,000 feet of proximity, showed that the AI could handle complex combat maneuvers without human intervention[12]. Although exact win-loss statistics were not disclosed, the AI's ability to safely and effectively engage in dogfights builds confidence in its combat abilities. This demonstrates that AI can be trusted to perform in scenarios that require split-second decision-making, a critical factor for human-machine teaming in any CCA. Despite this, there is still uncertainty about its performance in unpredictable, real-world combat situations. This suggests that VISTA's experiments are strong starts to having AI fully incorporated into military aircraft, and provides a solid basis for further testing and safeguards before full deployment in active combat roles.

Proposed at the 10th International Scientific Conference of Defensive Technologies, a new framework using AI called You Only Look Once (YOLOv5) helps enhance surveillance and target identification during military operations. The YOLOv5 model has been fine-tuned to detect and classify military objects such as tanks, artillery, and bunkers with high accuracy. The model achieved an average precision of 0.922 at a confidence threshold of 0.5, making it highly reliable in identifying targets from aerial surveillance footage[13]. YOLO demonstrates how AI can also be used to improve sensors and data gathering during operations. Its strength lies in its ability to process large datasets quickly and efficiently, enabling real-time decision-making on the battlefield. It can be implemented on a wide range of drones, including CCAs, without requiring significant computational resources. Incorporating YOLO into CCAs would be beneficial not only to data-gathering but also to fusion into the CCAs' machine-learning system and would assist in its adaptability in combat.

The NATO STO/AVT-251 Multi-Disciplinary Configuration (MULDICON) is an evolution of the Stability and Control Configuration (SACCON) UAV, designed to enhance agility and combat effectiveness. MULDICON features a 30° trailing edge sweep, reduced from SACCON's 53°, to improve maneuverability and internal payload. The configuration is powered by a single engine, delivering sufficient thrust for the specified mission requirement. MULDICON's design includes several improvements over SACCON, such as a smoother pitching moment curve and enhanced controls for better maneuverability[14]. The study's main focus on improving maneuverability and the layout for the engine and payload for their CCA design was an overall success, with some issues in high-altitude combat scenarios or low-altitude turns. However, the task group's ability to balance the internals of the aircraft with the CCA's ability to fly should be modeled when designing the optimal drone wingman.

The Mitchell Institute of Aerospace Studies demonstrates wargame examples where different CCAs' strengths are analyzed in the context of military operations. In Wargame Example 1, CCAs were used in counterair "sweep" operations to overwhelm and disrupt Chinese air defenses, paving the way for manned aircraft. The ability to deploy large numbers of expendable CCAs proved critical in neutralizing these threats, demonstrating the value of a diversified fleet where low-cost CCAs lead high-risk operations where advanced systems are unnecessary[10]. They can also be a defense mechanism in triggering enemy air defenses if a manned aircraft is being targeted and at risk of destruction, as modeled in Wargame Example 2[10]. This concept is further supported by complex network theory, where increasing the number of expendable CCAs improves the resilience of the network. Simulations show that deploying expendable CCAs with a node degree of 7 or higher equates to higher information-carrying capacity, in turn preventing the overloading of critical aircraft such as MAVs[5]. On the other hand, Wargame Example 3 reinforced the need for more advanced CCAs in suppression and destruction of enemy air defenses (SEAD/DEAD) missions. Higher-cost CCAs with advanced weapons systems and VLO technology need to be used for greater offensive success due to their ability to avoid enemy radars and destroy high-value targets[10]. Quantitative data from network clustering models suggest that CCAs equipped with stealth and advanced communication technologies, housing a clustering coefficient of 0.4 or above, maintain a 40% or higher probability of sustaining communication links during operations, ensuring reliable data sharing and coordination[5].

Discussion

When comparing these systems, several key aspects are highlighted and optimized in different studies:

Design Characteristics

Modularity relies entirely on the payload and survivability of the aircraft. As opposed to having different drones for different mission types, as detailed in studies conducted by Mitchell Institute, drone designs such as Samad and MULDICON contain payloads that can be easily arranged depending on the mission requirements. Survivability also plays a key role in the drone's modularity. For example, if a CCA is classified as VLO, then it will serve well in all operation types. However, it will also be more expensive, meaning that it would only want to be risked when a stealth mission is required, and instead, a drone of LO or no LO classification can be used.

For a drone to have high survivability, it has to have a low RCS. The materials and technology that enable aircraft to have low RCS are more expensive, however, calling back to the idea of using a VLO aircraft when absolutely necessary. In addition, the drone's ability to navigate operations and assist manned aircraft efficiently is based on its autonomous system. A high level of adaptability and machine-learning is required for combat scenarios where there is a need to avoid threats. A fraction of a CCA's survivability also lies in its ability to evade enemy aircraft with its speed and maneuverability, which will be addressed later.

The AI and autonomous system of CCAs will be a pivotal factor in enhancing their overall survivability and adaptability in dynamic combat environments. Skyborg exemplifies the cutting-edge potential of AI integration in CCAs. The system is designed to provide a high level of autonomy for military aircraft, allowing CCAs to perform complex missions with minimal human intervention. AI systems such as this excel in real-time data processing and decision-making, enabling the CCA to adapt to changing threats and mission parameters to fly. For instance, they can autonomously adjust their flight path to avoid detection, optimize payload deployment based on mission priorities, and even engage in defensive maneuvers if threatened, tying back to the importance of drone survivability. These systems' modular AI architecture can also be integrated into various airframes. This flexibility ensures that the AI can be tailored to the specific needs of the mission and allows for the management of multiple drones in a coordinated swarm, assisting in the CCA's modularity aspect.

Performance Metrics

The MULDICON drone showcases excellence in range, being able to reach an estimated 3000km without aerial refueling, which is highly beneficial for long-distance missions. Mitchell Institute also details that different CCAs have different ranges and can be used based on mission requirements. For example, while the Samad-3 has a shorter range of about 1900km in comparison to MULDICON, it has a larger payload and therefore is better at gathering data. The conclusion can be made that it is important to utilize different range capabilities depending on the military operation, as drones with long-distance capabilities will have a higher production cost.

As with range, the payload is dependent mostly on the price of the CCA. However, the payload has an impact on many other aspects of the drone, including modularity, speed, maneuverability, and sensors. This is due to the potential weight that can be added onto the CCA due to the size of the payload. The Samad drones had a robust payload space allowing for many sensors to be used in exchange for less maneuverability, while MULDICON has a smaller space but is quicker. They both detail specific payload layouts with space that is separate from the thruster area and built-in hardware. The ability to swap out these sensors and have a designated space for gathering data makes these CCA models highly modular. This is different from MAVs in that they do not need technology designed to protect a human pilot, allowing for more versatility in the payload arrangements.

Speed and maneuverability are vital factors for both survivability and mission success in combat scenarios. To evade enemy attacks, these qualities need to be substantial enough to survive in highly contested airspace. The VISTA system, as demonstrated in the ACE program, showcases the high-speed capabilities of AI-controlled drones. VISTA's ability to engage in dogfights at speeds up to 1,200 mph illustrates the potential for CCAs to perform high-speed intercepts and evasive maneuvers, which are crucial in both offensive and defensive air operations. The studies conducted by the Mitchell Institution suggest that not all drones in a CCA fleet need to prioritize speed. Instead, a diversified approach where some drones are optimized for high-speed engagement and others for endurance and stealth can provide a comprehensive capability set.

Technological Capabilities

Sensor technology is at the heart of the data collection of CCAs. Skyborg is equipped with an array of advanced sensor frameworks that enable it to operate effectively across multiple domains. These include infrared sensors, radar, and electronic warfare systems. The integration of Skyborg allows these sensors' data to also be used in conjunction with Skyborg's AI system, enabling it to make real-time decisions based on a wealth of data inputs. Similarly, YOLO incorporates an advanced sensor framework that leverages AI for object detection. The YOLOv5 algorithm has advanced speed and accuracy, making it ideal for military applications where quick and precise identification of critical targets—such as enemy vehicles, bunkers, or weapon systems—is necessary. This is especially valuable in surveillance and reconnaissance missions where the ability to distinguish between objects on the battlefield can impact mission outcomes. Pairing MULDICON and Mitchell Institute's studies on LO and VLO aircraft can allow for drones to stay stealthy and gather data for their Al. For the mission as whole, this will be the most effective way to return valuable results.

Effective communication systems are vital for CCAs, particularly in environments where data links may be compromised by electronic warfare. The Mitchell Institute's studies emphasize the need for resilient communication architectures that can maintain connectivity even in highly contested environments. Systems like Skyborg are designed with robust communication protocols that buttress data exchange between the CCAs, manned aircraft, and home base. YOLO further highlights the importance of AI-driven communication in coordinating actions across a network of unmanned systems. The real-time data processing needs to be shared across aircraft to coordinate attacks, avoid threats, and allow for the machine-learning to function as intended. With military technology constantly advancing, numerous jamming systems will be used by adversaries, meaning the USAF needs to continue to find ways to counter this threat. Interoperability is crucial for modern combat operations, where the ability to respond rapidly to new threats can determine mission success,

Human-machine teaming is the most important aspect and what makes CCAs unique from other military drones. The integration of AI systems like Skyborg into CCAs allows for a new level of collaboration between human pilots and autonomous systems. This relationship is not just about offloading routine tasks to machines but also leveraging AI to enhance human decision-making and operational effectiveness. These algorithms are designed to function alongside human pilots, providing support in complex combat scenarios where multiple tasks need to be managed simultaneously, freeing up the human pilot to focus on strategic decisions. This teamwork extends to scenarios where the AI can suggest optimal maneuvers and control themselves in high-risk situations where the MAV needs to be defended. VISTA addresses the problem of trust in this system. This autonomous technology working alongside humans in the air is very new to the military, and the machine learning needs to be tested in these systems before allowing them to work in real operations. Giving drones the ability to think for themselves is a risk, and VISTA's experiments test their ability to make accurate decisions based on different situations and protect the human aircraft simultaneously. By allowing the AI to take the lead in combat engagements, VISTA showcases how autonomous systems can not only support but also enhance the tactical capabilities of human pilots, creating a more formidable combat force.

Beyond procurement, CCAs provide cost advantages over MAVs by reducing life-cycle costs, maintenance complexity, and logistical demands. In low-intensity conflicts, their modularity simplifies maintenance and upgrades, and CCAs do not require complex life-support systems for pilots, reducing the maintenance complexity compared to MAVs[15]. However, in high-intensity conflicts, the need for survivability technologies, such as low-observable (LO) or very low-observable (VLO) capabilities, drives up the initial cost and requires more specialized maintenance[10]. However, compared to MAVs, the absence of pilot recovery and life support systems still offers a cost advantage[15]. Moreover, the expendability of certain CCA models designed for higher attrition reduces the long-term financial burden when compared to the loss of a manned aircraft. From a logistical standpoint, CCAs offer flexibility. Their ability to be rapidly reconfigured for different missions reduces the logistical strain associated with deploying diverse aircraft types[7]. However, maintaining a diversified fleet with different capabilities, such as drones optimized for speed, stealth, or endurance, requires a more sophisticated logistical network, especially in high-intensity conflicts. Overall, CCAs offer a flexible and scalable solution that minimizes long-term operational costs in diverse combat scenarios.

The increasing autonomy of CCAs raises critical ethical concerns, particularly regarding the use of AI in life-and-death decision-making. Allowing AI to control lethal actions presents risks, such as unintended collateral damage or privacy violations when gathering data[16]. Programs like VISTA help build trust in AI by testing it in controlled environments, but extensive trials are needed before granting full autonomy in combat[12]. A major ethical question is accountability, whether the developers or users of AI should bear responsibility for their actions, especially if unintended harm occurs. While human oversight remains essential, the trend toward greater autonomy complicates ethical accountability. As AI continues to evolve, it is crucial to address these ethical issues proactively. Future development must consider the consequences of allowing AI to fully take over potentially dangerous combat vehicles[16] and possibly prioritize embedding safeguards, such as human authorization for lethal actions and respecting civilian privacy. Without careful consideration of these concerns, we risk diminishing the human responsibility in warfare and undermining the moral implications of autonomous combat systems.

The findings in this study suggest that a diversified fleet of CCAs is essential for maintaining operational flexibility and effectiveness across a range of mission profiles. For example, drones like the Samad-3, with its robust payload capacity and long range, excel in precision strike missions but lack the maneuverability required for contested airspace seen in MULDICON.

The results from the wargame scenarios in the Mitchell Institute's studies highlight the strategic benefits of a diversified CCA fleet in military operations. The ability of expendable CCAs to reduce the threat on manned aircraft enhances operational flexibility and protects vital assets, as seen in Wargame Example 1 and Wargame Example 2[10]. The reduction in targeting of manned aircraft when supported by expendable CCAs shows the practical value of these systems as sacrificial assets that enhance the survivability of more valuable aircraft[5]. This aligns with the theoretical predictions of complex network theory, which emphasizes the resilience of distributed systems when lower-value nodes absorb potential threats.

Meanwhile, the findings from Wargame Example 3 confirm that more advanced CCAs, with superior stealth and communication capabilities, are essential for higher-stakes operations like SEAD/DEAD missions[10]. The increase in communication reliability in these systems underlines the importance of investing in higher-end CCAs to ensure continuous data sharing and mission success, especially in electronically contested environments[5]. These insights support the growing consensus in military aviation that an optimal CCA fleet must include both expendable and advanced models, each tailored to the specific needs of different missions.

Conclusion

The development of CCAs marks a critical advancement in military aviation, providing enhanced flexibility and operational effectiveness for the USAF. This study emphasizes the necessity of a mixed CCA fleet, with different models optimized for specific mission types. By incorporating a combination of expendable drones and advanced models for operations, the USAF can maintain air superiority across a range of combat scenarios.

Models and wargame scenarios highlight the strategic benefits of this approach. Expendable CCAs can shield manned aircraft in high-risk environments, while more advanced CCAs play key roles in complex missions, where more expensive technology is required for success. This combination ensures both cost-efficiency and mission adaptability, allowing the USAF to leverage the right aircraft for the right operation.

These studies demonstrate that a diversified fleet of CCAs, combining expendable drones with more advanced, specialized models, should be adopted to maximize operational flexibility, enhance survivability, and maintain the USAF's tactical advantage in modern warfare. The findings highlight that leveraging the strengths of different CCA types ensures that the USAF can adapt to a variety of combat scenarios while optimizing both cost efficiency and mission effectiveness.

Future Implications

Ongoing research and development will be essential for optimizing CCA design as global military powers continue to innovate. Future advancements should prioritize improving AI to enhance decision-making accuracy, strengthening communication systems to resist jamming and cyber threats, and refining modular designs for quick reconfiguration across different missions. Ethical considerations regarding the deployment of AI in autonomous combat systems will also need to be addressed to ensure responsible use.

The future of CCAs promises cost-effective, seamless integration with manned aircraft, enhancing air combat capabilities. AI and machine-learning will continue to evolve, shifting routine tasks away from human pilots and increasing mission efficiency. The deployment of a diversified, adaptable CCA fleet, tailored to specific mission needs, will be critical in maintaining air superiority and adapting to the ever-changing landscape of global security challenges.

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References

1 G. C. Allen and I. Goldston, *Center for Strategic & International Studies*, 2024.

2 J. A. Tirpak, U. L. Harpley and C. Gordon, *Air & Space Forces Magazine*, 2024.

3 S. Losey, *Defense News*, 2023.

4 S. Losey, *Defense News*, 2024.

5 J. Fan, D. Li, R. Li and Y. Wang, *Science Direct*, 2020.

6 J. A. Tirpak, *Air & Space Forces Magazine*, 2024.

7 J. A. Tirpak, *Air & Space Forces Magazine*, 2023.

8 C. Gordon, *Air & Space Forces Magazine*, 2024.

9 J. M. Eddins, *Airman Magazine*, 2024.

10 M. A. Gunzinger, L. A. Stutzriem and B. Sweetman, *Mitchell Institute for Aerospace Studies*, 2024.

11 J. Harper, *National Defense Industrial Association*, 2020.

12 S. Losey, *Defense News*, 2023.

13 A. Petrovski, M. Radovanović and A. Behlic, *Research Gate*, 2022.

14 C. M. Liersch, R. M. Cummings and A. Schütte, *DLR*, 2022.

15 T. Deneven, *Naval Postgraduate School*, 2014.

16 R. L. Wilson, *IEEE*, 2014.