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The future of the Air Domain at the advent of the Sixth Generation

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Introduction

The pervasive renewal of multi-layered strategic competition on global, regional and local scales, and the parallel re-emergence of the relative end of high-intensity conventional conflict as an immanent possibility, has promoted a widespread doctrinal, organizational and capacitive overhaul of, among others, the air military instrument, in order to maintain superiority in the third dimension. Indeed, the proliferation and refinement of increasingly integrated surface-to-air sensors and effectors capable of contesting or denying air dominance, imposing constant attrition on adversary air forces and going so far as to generate access-limiting bubbles (A2/AD – Anti-Access/Area-Denial), combined with significant cross-fleet modernization programs of peer and near-peer competitors poses fundamental challenges for the near future of air dominance. Conventional hostilities fought over the past fifty years, from the Six-Day War to the current conflict between the Russian Federation and Ukraine, indicate in parallel the strategic, operational, and tactical importance of the air military tool, highlighting the deleterious effects of a failure to achieve dominance of the skies: disarticulation of operational tempo, manoeuvre attrition, campaign stagnation, and exponential increase in casualties.

Based on this historical-doctrinal awareness and considering the profound transformation of the air battlefield and the gradual obsolescence of air superiority fighter fleets, many Air Forces, especially Western ones, have inaugurated development programs to equip themselves with up-to-date aircrafts capable of performing at their best in air-to-air combat, surviving in the increasingly lethal third dimension, and penetrating multilevel air defence systems. This new, sixth generation of fighters aims to introduce considerable technological innovations that are set to radically transform the use of the air instrument and potentially decisively tilt the balance of power in military competition. This Focus Report intends to first illustrate the elements that differentiate the previous five and a half generations (including the so-called 4.5 generation, or "half-generation") from one another, proceeding then to analyse the technical and doctrinal trends common to the fighters still under development, and then to expose the characteristics of the main element of innovation in the operational concept underlying the creation of the aircraft, namely the use of gregarious drones in a system of systems. Finally, the status of the major sixth-generation aircraft development programmes will be outlined, with a specific focus on the U.S. Next Generation Air Dominance

(NGAD), the international Anglo-Italian-Japanese Global Combat Air Program (GCAP), and the Franco-German-Spanish Future Combat Air System (FCAS) project.

The generational evolution of air superiority aircraft

In order to better highlight the evolutionary contribution pursued in sixth-generation programmes, it seems appropriate to identify as a premise the main capability, technical and technological improvement that have led to contemporary fleets of air superiority aircraft over the decades. The first generation of fighters acquired the most significant innovations introduced on military aircraft during the Second World War, in particular jet engines capable of generating significantly higher speeds than turboprop fighters, albeit still below the speed of sound. Such aircraft made their appearance during the last years of the Second World War (the German *Messerschmitt* Me-262 fighter is emblematic in this respect) and were the main protagonists of air operations during the Korean War (1950-1953). The second generation of fighters is introduced from the mid-1950s onwards, a period that marked a significant development in the field of aviation technology. The second-generation military aircraft benefited from improved aerodynamics and propulsion thanks to the introduction of swept wings (already present on some pioneering first-generation aircraft) and the afterburner, the latter capable of producing a significant increase in thrust and allowing the aircraft to operate in transonic regime, i.e. close to the speed of sound. The advances in integrated on-board electronic systems and weaponry were even more remarkable, witnessing the inclusion of navigation radar, rudimentary fire control systems and the first semi-active or infrared (IR) guided air-to-air missiles, such as the AIM-9 Sidewinder. These innovations enabled a significant extension of the aircraft's detection and engagement capabilities, which coupled with improved aerodynamic performance marked the beginning of a radical change in the conduct of air duels, hitherto conducted exclusively with direct fire weapons such as machine guns and automatic cannons.

The third generation of fighters, introduced in the early 1960s, marked a considerable shift in the tactical use of military aircraft with the introduction of the concept of the multi-role fighter, being the latter an aircraft capable of performing both the task of an interceptor (an aircraft specially built to reach and engage enemy aircraft) and that of a fighter-bomber. The elevation of guided air-to-air missiles to the rank of primary armament also made it possible to extend the engagement range beyond the field of view (BVR – Beyond Visual Range), while on-board automatic weapons were relegated to an ancillary role and used exclusively for very short-range dogfight. In the avionics and aerodynamic segment, the generation witnessed the temporary emergence of variable-sweep wings, entailing the aircraft's ability to modify the position of wings during flight, swept back and then returned to its previous straight positionon according to the speed and cruising altitude. The fourth generation of fighters, many of which are currently operational after upgrades, entered in service from the mid-1970s. The aerodynamics of aircraft belonging to this generation are characterised by an emphasis on manoeuvrability rather than speed, in order to make the aircraft capable of performing manoeuvres with a high gravitational acceleration coefficient (G force). This was made possible by the introduction of the digitalised fly-by-wire flight surface control system, which allowed the removal of the previous hydraulic component unsuitable for withstanding such extreme stresses. The most relevant peculiarities of the fourth-generation aircraft also concern the electronic equipment that, thanks to the miniaturisation of components and circuits, has made the aircraft a platform suitable for carrying and employing a wide range of sensors, both active and passive, aimed at improving its intelligence, surveillance, reconnaissance, acquisition (ISTAR) and target engagement capabilities. The use of such electro-optical and infrared sensors is then complemented by the use of intelligent munitions, such as laser-guided or GPS-guided air-to-air and air-to-surface weaponry. The complexity of the on-board systems is designed to integrate the airborne platform into the network of sensors and computers theorised by the Network-Centric Warfare doctrine, which aims to exploit the potential inherent in the information revolution produced by the digital age to provide the most technologically advanced side with a decisive strategic-operational advantage, transforming the aircraft into a node in the battlefield's Command, Control and Communication (C3) network.

On the contrary, the transitional nature of the 4.5 fighter generation can essentially be traced back to the substantial cuts in military spending that followed the end of the Cold War. Unlike previous generation jumps, this intermediate category does not introduce any structural changes compared to the fourth-generation aircraft, presenting an upgrade and improvement of technologies already present on these aircraft. Among these, the most significant addition is the integration of Advanced Electronically Scanned Array (AESA) radars, which substantially increase the detection and target tracking capabilities, giving aircraft an albeit limited Airborne Early Warning capability. Furthermore, the implementation of connections between systems via Tactical Data Link (TDL) further emphasised the centrality of this generation's aircraft in a net-centric battlefield. Although these innovations bring significant capacitive improvements to the aircraft, they do not entail doctrinal changes that would profoundly alter the use of the military air instrument. In terms of aerodynamics, the delta-canard wing, common to several 4.5-generation fighters such as the Dassault Rafale, the EFA-2000 Typhoon and the JAS-39 Gripen, is notable. Turning to fifth-generation fighters, the few models of which have been introduced since the mid-2000s, the main feature is stealthiness, i.e. the ability to reduce radar signatures through the reduction of the equivalent radar cross section (RCS) achieved through the use of radar-absorbent materials (RAM), specific paints and through the careful design of the aircraft’s geometry and shapes. Fifth-generation fighters resort to removing the external sub-wing mounts for armament and the pods on the lower section containing the navigation and targeting systems, integrating these resources directly into the fuselage and internal bays. The adoption of advanced engineering solutions inherent to engine cooling and exhaust gas concealment also helps reduce the thermal signature of the aircraft, which thus becomes better protected against infrared-guided munitions. The primary objective is to increase the aircraft's survivability, making it more difficult to detect and engage both by other aircraft and by surface-to-air missile systems. The on-board electronics are characterised by the most advanced C3 systems and by a suite of the latest generation omnidirectional sensors, aimed at amplifying pilot’s situational awareness, also thanks to the real-time sharing of a large amount of information collected by other weapon systems. From an aerodynamic point of view, these aircraft maintain prolonged periods of flight in supersonic regime without the use of afterburners, the so-called supercruiser (already employed by Concorde), although this comes at the price of high fuel consumption.

Compared to previous generations, the sixth generation is more correctly configured as a sixth-generation framework, and not just a fighter. This is due to the presence of several other remotely piloted aircraft, called Collaborative Combat Aircrafts (CCAs), which would flank the aircraft both for air-to-air combat and for conducting ground-based targeting (strikes), particularly in the suppression or destruction of enemy air defences (SEAD/DEAD). In this perspective, these drones would assume the role of vectors for the transport of sensors and/or effectors remotely controlled and interconnected to the aircraft through the use of artificial intelligence (AI), which would provide decision-making and executive support to the pilot thanks to the collection and processing of a huge amount of data in a minimum of time. Lastly, the relevant innovations brought about by this new generational leap do not preclude cooperation with the platforms of previous generations, which are in any case deemed to remain in service for several years, but on the contrary determine the integration of the sixth-generation framework into an intergenerational net-centric structure based on the increasingly close collaboration between manned and unmanned assets (MUM-T – Manned-Unmanned Teaming).

The system of systems: the sixth-generation fighter

Although there are a rather limited number of illustrations, scale models and demonstrators associated with the sixth-generation fighter programmes, it is possible to identify some common trends among the projects that hint the possible distinctive features of the aircraft representing the central node of the system. First of all, there is an accentuation of the extremely soft and tapered shapes already typical of fifth-generation fighters, which allow the aircraft to deflect the radar signal and keep its position concealed up to very short distances from the source. Since increasing the aircraft's aerodynamic performance is a common primary objective in the development of new-generation fighters, the design features a significant enlargement of the wing surface, in which the fuselage profile almost disappears completely (integrated fuselage). The wingspan of the aircraft is significantly increased and the wing, apart from the differences between the various models, appears to follow a cropped delta shape. Another element deserving special attention is the configuration of the aircraft's rear stabilisers, both the vertical ones, either completely absent or very angled in most illustrations, and the horizontal stabilisers, which are often removed. This solution is, moreover, coherent other stealth aircrafts, such as the B-2 Spirit bomber, which is completely devoid of any winglets whatsoever, or the F-22 Raptor, which has highly inclined drifts to minimise radar signature. One part of the aircraft that does not currently appear to have an unambiguous conformation in the various concepts released to date is the canopy. Some depictions of the US sixth-generation NGAD fighter aircraft show a rather small and barely curved canopy, elliptical or even rhomboid in shape, while the GCAP demonstrator, unveiled by the Anglo-Italian-Japanese consortium in the summer of 2024, has a more classical shape. Given the aircraft's required performance in terms of speed and altitude, the polycarbonate used for the canopy also needs special treatment.

As well as the aerodynamic connotations, one of the most important innovations is the aircraft's type of propulsion, which is directly related to the tactical use for which it was likely conceived. In fact, sixth-generation fighter aircraft programmes are intended to compensate for the technical and design limitations of the previous generation jets. Indeed, both the Advanced Tactical Fighter (ATF) and the Joint Strike Fighter (JSF) programmes, both dating back to the mid-1990s, were aimed at producing a fighter capable of evading airborne detection systems for use during a hypothetical war in Europe or in the

Mediterranean area, where the US and the Allies could rely on NATO's vast network of airport infrastructures. The two fighters derived from the aforementioned programmes, the F-22 Raptor and the F-35 Lightning II, were consequently designed to carry out short-range sorties, taking off from equipped airfields, carrying out air superiority missions or targeted strikes of short duration and quickly returning to base to refuel and rearm. The consequence of this tactical doctrine had been the limitation of the aircraft's range and load-carrying capacity, due to the removal of armaments and additional sub-wing tanks that inevitably compromised stealthiness, sacrificed to improve the aircraft's ability to penetrate air defences. The emergence of new strategic competitors of primary importance in the Indo-Pacific regional quadrant has compelled the institutional and industrial players involved in the development programmes to reflect deeply on the attainability of air superiority in an area where the extent of the theatre of operations, the peculiar environmental conditions and the widespread presence of A2/AD bubbles represent technical-operational challenges that are difficult to tackle with the aircraft currently in service. The increased range, speed and payload of the fighter were therefore prioritised in the design phase. Indeed, the sixth-generation fighter needs to cover longer distances at supersonic speeds while carrying a greater payload of armaments. Although concrete clues as to what the propulsion solution might be are rare, it seems that we may be moving towards the adoption of an Adaptive Cycle Engine (ACE), i.e. a propeller capable of maximising performance in mixed flight conditions. This would allow the aircraft to operate in subsonic, transonic and supersonic regimes even for long periods without over-stressing the components and above all by making the engine more efficient minimising fuel consumption, with direct positive effects on the aircraft's operational range. The conceivable solution for the US programme, the only major one to have released more detailed information on the subject, seems to be the XA100 three-stream ACE engine, developed by General Electric. This propulsion system, which has already been considered as a possible replacement for the Pratt&Whitney F135 engine on the F-35 Block 4 version, envisages the use of a third bypass flow in addition to those generated by the fan and turbojet. This flow follows an external path parallel to the secondary flow and can be used alternatively either to increase the aircraft's thrust in maximum power mode or as an additional method of cooling and improving engine efficiency. Reiterating once again the speculative nature of this information due to the lack of reliable data available, it was estimated that such a propulsion system could give the fighter a maximum speed of Mach 2.2-2.5, or almost 3,000 km/h.

Engine cooling, at least for the NGAD programme, is, however, the focus of concern for both engineers and the US Air Force (USAF) Joint Programme Office, with the possibility of equipping the sixth-generation fighter with a new cooling system proposed by Collins Aerospace known as the Enhanced Power And Cooling System (EPACS), designed to run at 80 kilowatts for an indefinite time through all elements of the flight envelope, ensuring a coolant temperature of around 15° C. Although a number of technical obstacles remain (especially inherent to the weight of the system), increasing the cooling capability of the fighter seems imperative for at least three reasons: firstly, to improve engine performance while preserving its components to extend its operational life; secondly, to ensure the operation of an increasingly rich suite of electronic equipment central to the aircraft's combat capabilities; and lastly, to reduce the aircraft's thermal signature as much as possible, in order to make it even less detectable to the most advanced InfraRed Search and Track (IRST) systems. Finally, it should be pointed out that, after initial uncertainty, it does not appear that the engine prototypes currently being studied are equipped with vectored thrust, which would suggest ruling out the possibility of an embarked version of the aircraft with short take-off and vertical landing (STOVL) capabilities being developed.

The maintainability of the aircraft and the preservation of its advanced technical features were also subject to a thorough review, especially as regards the NGAD programme, with a view to possible deployment in the Indo-Pacific theatre. The very delicate radar-absorbing material must in fact be adapted to avoid premature deterioration due to the radically different humidity, salinity and temperature conditions from those found in the European climate. In comparative terms, according to the US Government Accountability Office, more than 70 per cent of the total costs for the fifth-generation JSF programme are attributable to maintaining the fleet at operational readiness, compared to less than 30 per cent for the acquisition of the assets. At the same time, the transport capacity of the sixth-generation aircraft appears not yet defined, although the increase in payload remains one of the critical requirements of the new fighter. Exactly like its fifth-generation predecessors, the aircraft will conceivably make extensive use of internal bays located in the lower and lower-side sections of the fuselage. Within these housings will be a panoply of different types of air-to-surface (GPS or laser-guided) and air-to-air (both IR-guided and radar) weaponry, including, in the US case, Northrop Grumman's Stand-in Attack Weapon (SiAW) and Lockheed Martin's AIM-260 Joint Advanced Tactical

Missile (JATM). It seems likely that even some types of small drones can be crammed into the bays, allowing the aircraft to release them at the most opportune moment as Air Launched Effectors (ALE).

From what can be assumed from the graphic concepts that have emerged so far, the cockpit will be considerably narrower, drastically reducing the pilot's physical vision. The latter, however, will be able to rely on the sensor fusion mode already experimented on aircraft such as the F-35, with the widespread presence of cameras and sensors throughout the fuselage to ensure an immersive experience for the pilot, breaking down the visual obstacles constituted by the cockpit walls, creating a sort of augmented reality directly in front of the operator's eyes through the display integrated in the helmet visor (HMDS – Helmet-Mounted Display System). Such an extended field of view provides the pilot with a more detailed and constantly updated operational picture, enabling him to identify potential threats to the aircraft early enough and make critical decisions in shorter time. The pilot's situational awareness will be increasingly enriched by the use of the Tactical Combat Cloud, a computer architecture designed to collect, process and disseminate data to a number of authorised military users who access this data centre via the asset or the weapon system they are employing. Such a digital resource focuses on the perfect synergy between platforms belonging to different Armed Forces engaged in all operational domains, making the collection and sharing of information during so-called Joint All-Domains Operations (JATO) extremely flexible. This tenet is a sublimation of the operational principles of Network-Centric Warfare, which employs the instantaneous transmission of information gathered by the nodes of a sensor network to maintain a high battle rhythm, creating an increasingly transparent battlefield within which the various blue and green assets can benefit from such an information asymmetry compared to the adversary that any decision-making process is rendered useless, as they are unable to keep up with the frenetic evolution of tactical events. A system of similar sophistication, combined with the computational capability of AI, has generated a lively discussion as to whether the pilot should be removed from new-generation aircraft altogether, or kept on board, but with different tasks. In this regard, the concept of the optionally manned aircraft has increasingly emerged, i.e. a fighter aircraft that may present a station for a human operator but not necessarily occupied by the same. In all likelihood, the automation of certain navigation systems would allow the operator to handle the collaborative unmanned assets more freely, turning him closer to a Weapon System Officer (WSO) than a pilot. Although the hypothesis could be an intermediate step in the development of the fighter in order to reduce costs and development time, it is conditioned both by the limits of today's technology and by ethical-legal considerations, particularly if the machine were to be enabled to authorise and execute kinetic actions according to a human-out-of-the-loop decision-making process, meaning without any form of human supervision or approval. Despite the significant focus on the aircraft per se, the sixth-generation concept appears to transcend for the first time the fighter-only improvements, placing specific attention on a network of assets and capabilities outside the aircraft and in particular on so-called wingman drones.

The systems of the system: the wingman drones

The most distinctive feature of the sixth-generation fighter is undoubtedly the presence of a variable number of Unmanned Aerial Vehicles (UAVs) directly interconnected to the aircraft. These drones, called Collaborative Combat Aircrafts (CCA), or also Loyal Wingman, can be classified into different types depending on a number of characteristics and represent the critical element of the strategy aimed at rationalising and simplifying the sustainability of expeditionary air operations in contexts characterised by adverse geographical factors and a high level of expected friction. The primary objective remains the ability to penetrate A2/AD bubbles, i.e. areas of greater or lesser extent within which access and the conduct of air-to-land or air-to-sea operations is rendered prohibitive by the massive presence of an articulated and redundant multi-level defence architecture. To this end, the US Department of Defence developed a specific doctrine in 2010, primarily tailored on a littoral theatre such as the Indo-Pacific, known as *AirSea Battle*, emphasising the need for advanced assets prepared to survive in a highly contested operational environment, where the threat to air supremacy is manifested through platforms designated for the creation of kinetic effects, such as anti-aircraft missile batteries, drones and adversary aircraft, and instruments designed to conduct operations in the electromagnetic environment. CCAs would precisely have the task of neutralising or at least degrading the integrated air defence systems and avoiding exposing the pilots and the most valuable and assets to the risk of being detected and shot down. To perform this task, these drones would form, together with the sixth-generation fighter, an AI-controlled system of systems within which elements with a different degree of independence would pursue the same objective in different ways. In this model, the fighter would thus behave like a quarterback in an American football team, setting a strategy and directing the offensive line, but leaving the individual players a certain degree of autonomy.

CCAs can therefore play the role of both sensors and effectors and can be classified according to their operational expendability, i.e. the number of missions they are expected to perform. According to this criterion, a distinction can be made between Expendable CCAs, which are low-cost and designed to perform very few missions, or even only one; Attritable CCAs, which are designed to be salvageable and to perform more missions, but which, if lost in combat, would not represent a serious loss; and Exquisite CCAs, top-notch aircraft of considerable cost, which are to be used essentially as conventional aircraft and whose destruction in combat is hardly acceptable. The operational integration and simultaneous deployment of wingman drones from the three categories aims to generate that affordable mass capable of saturating, surprising and neutralising adversary defences by deploying and distributing diversified capabilities on individual assets, functional to conduct intelligence activities, surveillance and reconnaissance (ISR – Intelligence, Surveillance and Reconnaissance), Electronic Warfare (EW) and counter-EW, ground attack, DEAD/SEAD and even air superiority missions, engaging enemy aircraft with air-to-air armament (defined as UCAV – Unmanned Combat Air Vehicle). The line of CCAs proposed by General Atomics, a company that already produces the MQ-1 Predator and its iterations, represents well the concept of a modular platform through the Gambit family of systems. These CCAs all employ the same propulsion system but mount a different body depending on the mission profile the drone is called upon to perform. Therefore, while Gambit 1, 2, and 4 are used as ISR, air superiority and combat recon assets respectively, Gambit 3 is a trainer capable of playing the role of an aggressor fighter during dogfight practice simulations for pilots.

The ability of CCAs to take off from very short runways or the possibility of them being launched in flight, as ALEs, from other stand-off platforms, even non-stealth ones such as the F-15EX Eagle II, tactical transporters or strategic bombers, allows the air forces to assume a more dispersed and capillary forward posture, useful for preventing surprise attacks against forward deployed infrastructures when air assets are at their most vulnerable. In this regard, the theatre logistics of these tools should be taken into account, adapting them to a lean and efficient model, according to an operational concept called Agile Combat Employment (ACE). This doctrinal assumption, inspired again by the Indo-Pacific theatre, is based on the ability to deploy and, if necessary, risk assets in an unpredictable and short timeframe in a plurality of forward locations, including rather remote and poorly equipped sites. A distributed, dispersed and elusive approach, more suited to the characteristics of the theatre of operations, is therefore preferred to mass concentration. The objective is to conceal their assets by removing them from the ISR capabilities of hostile forces, without renouncing deploying them close to the area of operations, either for combat or deterrence purposes. In order to assume such a posture, it is necessary to move from large, conspicuous and complex infrastructures to essential tactical outposts, which are as easy to conceal as they are to maintain in a state of readiness and efficiency, with a reduced presence of personnel (Resilient Forward Basing). Provided they maintain as small a logistical footprint as possible, CCAs are therefore inherently suited as platforms to become the cornerstone of ACE. Their unmanned nature significantly reduces risks and logistical requirements, while their ability to team with manned and unmanned assets allows for increased efficiency and kill-chain extension by multiplying both sensors and effectors. Lastly, having a digital structure based on an open architecture, modifying the CCAs' software requires relatively few human and material resources, which makes it possible to improve the resilience of wingman drones in an environment saturated with a large number of threats of a different nature. The potential of machine learning makes it possible to systemise information and data collected during previous missions and from a large number of other platforms in order to devise compensatory strategies to increase the UAV's chances of survival during subsequent operations.

The significant strategic, operational and tactical advantages provided by a fine integration of a limited number of manned aircraft with a scalable and diverse fleet of collaborative drones has promoted widespread experimentation with CCAs. These appear to incrementally define and redefine, with the synergistic and convergent advancement of robotics and AI, the characteristics that will outline the sixth generation, projecting a future less focused on the capabilities of the individual trim and plausibly enhancing the integrated multi-effect potential of a multi-platform aerial device.

The US perspective: NGAD and F/A-XX

The need for a sixth-generation fighter was perceived by the US Department of Defence after 2010. The numerical inadequacy and progressive obsolescence of air supremacy aircraft, attributable to the allocation of large portions of the budget for the acquisition of more deployable assets in the asymmetrical conflicts of that period and the merely hypothetical nature of a possible conventional peer-to-peer conflict, imposed a review of the US Armed Forces' ability to maintain dominance in the third dimension, especially in a theatre of growing strategic competition such as the Indo-Pacific. In 2014, the Defence Advanced Research Projects Agency (DARPA) published a study, called the *Air Dominance Initiative*, in which it emphasised the need to renew and expand the fleet of F-15C/D Eagle fighters and F-22 Raptors, not exceeding a total of 370 units, of which only a percentage not higher than 70 per cent were in a condition of effective operational readiness. This need was further reiterated in 2016 by a study published by the USAF, entitled *Air Superiority 2030*. In a similar fashion, the US Navy also started an acquisition programme aimed at securing a replacement for the F/A-18 embarked fighter and flanking the F-35C. The research and development programmes for the two aircraft were therefore named Next Generation Air Dominance (NGAD) and F/A-XX, respectively.

With more than 4.2 billion dollars already allocated to 2024 for research and development activities and a projected expenditure for the five-year period 2025-2029 exceeding 19 billion dollars, the NGAD is expected to be in service by 2030, thus constituting, together with the F-22 and the F35A a triad of fifth- and sixth-generation stealth fighters on which the USAF's capabilities to maintain control of airspace in the area of operations and to conduct Offensive Counter-Air (OCA) missions, aimed at imposing superiority or air supremacy above and below the battlefield, will hinge. In order to prevent a single company from rising to the rank of monopolist in the procurement process, procurement was also structured according to an innovative tripartite scheme, aimed at ensuring that three different contractors handle the design, production and logistics of the aircraft, with the aim of guaranteeing a high level of competition and thus, theoretically, product quality. A demonstrator of the aircraft was reported to have carried out an initial flight test as early as 2020, but in the summer of 2024 the programme ran into a downward revision of the spending forecast due to the hypertrophic growth in the budgets required to complete the development phase. With an estimated unit cost of around 300 million dollars, the NGAD would in fact risk becoming too valuable and difficult to replace to run the risk of it being lost in combat, while it has been pointed out that a number of capabilities envisaged for the fighter could also be expressed by the CCA alone, whose parallel programme envisages additional allocations of almost 9 billion dollars over the same period. A possible solution to this impasse could be a possible light version of the NGAD, in some respects more akin to an extended upgrade of the F-35 than a new fighter aircraft proper. This new aircraft, being studied by the USAF, would in fact be smaller in size due to the reduced requirements it would have to meet, particularly with regard to electronic warfare and payload capabilities.

Regarding the F/A-XX Programme, back in 2012 the US Navy issued a request for information for an embarked air superiority fighter with limited multi-role capabilities, due to enter service in 2030. The Navy Aviation Vision 2030-2035 policy document, released in 2021, placed special emphasis on the next-generation fighter's range requirement, defining the F/A-XX as one of the two future pillars of the US Carrier Strike Group's (CSG) air-to-air projection capability, with the other pillar being the F-35C. Other primary requirements were an increased payload, the presence of a suite of both active and passive sensors, and the ability to deploy the highest performing and most modern long-range air-to-air weaponry, including the AIM-174B missile, an air-to-air version of the RIM-174 Standard Extended Range Active Missile (ERAM) surface-to-air/surface launcher, better known as Standard Missile 6 (SM-6), currently operated by the F/A-18F. Such features were deemed necessary to integrate the new asset into the operational concept of Distributed Maritime Operations (DMO), a doctrinal framework for conducting distributed maritime operations in the vast ocean expanses of the Pacific. Although it was announced that the programme was ready to move into the design maturity phase in December 2023, the constraints imposed by the draft Fiscal Year 2025 budget forced the US Navy to postpone the allocation of additional funds of approximately 1 billion dollars, previously earmarked for the development of the sixth-generation embarked fighter, in order to prioritise the maintenance of the assets already in service. This decision meant postponing any further progress in the F/A-XX procurement process to the next fiscal year, casting doubt on the future and timing of the programme.

The Anglo-Italian-Japanese perspective: GCAP

The Global Combat Air Program stems from a pre-existing British programme for the development of a sixth-generation fighter called the Tempest programme, launched in 2015 with the aim of replacing the EFA 2000 Eurofighter Typhoon air superiority fighters by 2035. As outlined in the Combat Air Strategy published by the UK Ministry of Defence in 2018, the Tempest fighter would become the main asset of a system of systems consisting of UCAVs and drones of smaller size and cost capable of swarming. The document also emphasised the desirability of seeking other international partners in order to launch a joint development programme to improve the interoperability of weapon systems between allied nations, contain costs and facilitate the collective growth of the European defence industry, as was previously the case for the development and acquisition of the Eurofighter. In late 2020, the governments of Italy, Sweden and the United Kingdom signed a Memorandum of Understanding for the joint development of the new fighter, establishing an equal sharing research and development costs. The following year, the programme entered the Concept and Assessment Phase, with the UK government approving an allocation of around 340 million pounds to BAE Systems to develop the design of the new fighter aircraft. In 2022, the programme underwent radical changes in terms of participating nations: the Governments of Italy, the United Kingdom and Japan (the latter already in talks with the UK for an agreement on the development of collaborative drones and about to launch an autonomous programme for a new-generation aircraft temporarily named F-X) signed an agreement for the Global Combat Air Program (GCAP), aimed at the development and production of a sixth-generation fighter aircraft to deepen defence cooperation, scientific and technological collaboration, integrated supply chains and further strengthen the common defence industrial base. The aircraft is scheduled to enter service in 2035, replacing the approximately 90 Japanese *Mitsubishi* F-2 fighters and over 200 Typhoons in service with the Italian *Aeronautica Militare* and the British Royal Air Force.

Further details regarding the two special transnational organisations established to lead the programme, one of an intergovernmental nature and one for industrial cooperation, were outlined in a trilateral agreement signed in Tokyo in December 2023. A first mock-up of the fighter was presented by the three leading companies of the project (Leonardo, BAE Systems and Mitsubishi) at the Farnborough International Airshow in 2024, while the first flight of a demonstrator is scheduled for 2027. With regard to the aircraft's subsystems, the propulsion system will be jointly developed by Avio Aero, Rolls Royce and IHI Corporation, while ELT Group and Mitsubishi Electric Corporation will design the on-board electronic systems. Finally, MBDA UK and MBDA Italy, again in conjunction with Mitsubishi Electric Corporation, will work together to develop the fighter's combat system and effector component.

The Franco-German-Spanish perspective: FCAS

The need to replace the Dassault Rafale fighters of the *French Armée de l'Air et de l'Espace* and the Typhoons in service with the German *Luftwaffe* has also prompted France and Germany to undertake numerous international cooperation initiatives in the defence industry sector, extending them to other operational domains in order to renew some of the main assets of their Armed Forces. In 2018, the Chief of Staff of the *Armée de l'Air* and the Director of the Planning Department of the German Ministry of Defence in fact signed an agreement containing the capacitive requirements that the aircraft would have to possess, with the emphasis on the importance of long-range air-to-air combat and ground attack capabilities. Similarly, stealthiness, interoperability with other NATO platforms and the Atlantic Alliance's C3 systems, as well as the ability to take off and dock on a conventional aircraft carrier were indicated as equally important requirements. In the same year, the two governments launched the FCAS programme, Future Combat Air System (SCAF - *Système de Combat Aérien du Futur* in French), presenting it as an indispensable initiative for the security of their respective countries and a considerable step towards achieving European strategic autonomy. The French company Dassault Aviation and the European-registered company Airbus have in parallel announced a technical collaboration for the development of the project. In contrast to the Anglo-Italian-Japanese GCAP consortium, however, the shares in the programme are not equally divided between the two countries: France (and thus Dassault) has assumed the role of project leader, with the predominantly German-driven Airbus Group as a minority partner. This corporate architecture was conceived in complementarity with another Franco-German defence initiative, namely the joint development of a new Main Battle Tank (MBT) known as the Main Ground Combat System (MGCS), an initiative that would instead be German-led. Mutual misgivings concerning such an overall configuration, as well as marginal criticalities concerning the allocation of intellectual property and design authority, led to a delay in the start of the programmes, resulting in a postponement of the planned date of entry into operational service of the sixth-generation Franco-German fighter, postponed from 2035 to 2040.

Despite initial difficulties, the programme officially started in 2019, when the two governments granted an initial allocation of 65 million euros to Dassault and Airbus to begin a preliminary feasibility study. In the same year, Spain also decided to join the programme, in urgent need to replace the F/A-18A/B Hornet acquired over four decades ago, the Eurofighter and AAV-8B Harrier of the *Armada Española*. In 2020, the programme entered Phase 1A of the research and development process, with initial funding of 155 million for Airbus and Dassault. At the same time, the programme was structured into seven pillars in order to identify the individual companies responsible for producing the aircraft subsystems. Specifically, the development of the engine has been entrusted to the French company Safran and the German MTU Aero Engines, while the CCAs and other remote system effectors will be designed by MBDA France and Airbus, which in turn will cooperate with Thales for the development of the platform's combat cloud. Finally, the latter will jointly develop the sensors and on-board electronics with the Spanish company Indra. Although it is not yet clear which company will take over the design of the stealth components of the aircraft (especially the radar-absorbing material), the countries participating in the programme aim to conduct the first flight of a demonstrator by 2029.

The other projects on the sixth-generation fighter

Although the conceptual, design and production requirements for new-generation aircraft are mainly the prerogative of Western countries for technological, technical and economic reasons, other nations have also started to reflect on the desirability of developing similar weapon systems. This decision originates primarily from the desire to stimulate the national economy through substantial public investment in high-tech heavy industry, combined with ambitions for strategic autonomy in the context of revised national security policy documents. This is the case of Turkey, which, following its exclusion from the JSF programme, has diverted significant funding to the national defence industry, setting itself the goal of transitioning to fully autonomous production of components for weapon systems in service with national Armed Forces. In February 2024, the first demonstrator of the TF *Kaan* fifth-generation fighter aircraft, which aims to use exclusively Turkish-sourced components although the engine is still produced by the American General Dynamic, carried out its first flight test, hailed by national institutions as a fundamental step towards Turkey's independence in the defence sector. At the same time, the government in Ankara has stated that it has begun exploring the possibility of launching a programme for a sixth-generation fighter, perhaps integrating AI on an updated version of the *Kaan*. Notably, Turkey has already achieved significant success in the development and domestic production of remotely piloted aircraft, such as the well-known *TB2 Bayraktar*, produced by *Baykar*, and the *Anka* family of UAVs, produced by the state-owned Turkish Aerospace Industries (TAI). The latter include ISR and UCAV assets potentially suitable for integration into a sixth-generation fighter system of systems.

Another country that has shown concrete interest in the indigenous development of a sixth-generation fighter is Pakistan. After the positive experience of the JF-17 Thunder, a fourth-generation aircraft developed jointly with Chinese aerospace companies, the government in Islamabad is reportedly contemplating the development of a sixth-generation fighter, possibly intensifying cooperation with the People's Republic of China. Among the hypotheses contemplated in recent months is the acquisition of the J-31, a fifth-generation multi-role fighter currently being prepared by Shengyan Aircraft Corporation. It is not ruled out that these planes could be initially acquired and, subsequently, undergo retroactive engineering adaptations (retrofitting) to enable their integration with AI and, thus, with wingman drones.

Conclusions

The continuous and ever-faster evolution of strategic competition for technological and operational superiority in the aviation domain is driving the elaboration of new technical and operational requirements for the fleets of the near future. The various programmes aimed at developing sixth-generation aircraft appear in this light to seek a solution to the dilemmas posed by the current battlefield in the third dimension, from the possibility of conducting longer-range missions to that of deploying a multi-platform distributed aerial device capable of disrupting adversary defences by limiting the impact of friction typical of conventional high-intensity warfighting.

It is precisely this latter feature, promoted by a doctrinal revision focused on the survival, sustainability and resilience of the air military instrument in the event of hostilities between peer or near-peer competitors, that currently appears to favour, in combination with an increasing synergy between robotics and AI, the development and experimentation of the gregarious drone component rather than the main aircraft. The test campaigns conducted for the purpose of technological maturation and definition of doctrinal concepts for the deployment of CCAs have also often aimed to exploit the advanced net-centric capabilities already provided by Lockheed Martin's JSF, which is widely deployed by the USAF, US Navy and US Marine Corps (USMC) in these activities. The increased traction of collaborative drone programmes, especially in the US context, promoted by significant achievements in terms of platform autonomy and platform integrability with diverse sensors and effectors, combined with the increasingly high-cost projections for the single sixth-generation aircraft currently appear to be outlining a rather uncertain outlook on the future configuration of the system of systems and point to some central issues for their definition.

First and foremost, although the ideal characteristics of the next generation of air superiority fighter are, on the whole, quite clear and can be summarised as further, faster, higher and with a greater payload, their commutation into specific technical requirements tends to map out an aircraft whose acquisition, operation and maintenance costs are difficult to sustain. The size, the engineering complexity and the consequent logistics of adherence for such an asset also identify some incompatibility profiles with respect to a re-emergence of high-intensity conventional warfighting in which technological supremacy may not be rapidly converted into military success, generating a clash that is not necessarily static, but possibly also manoeuvring and dynamic, characterised, however, by significant human and material friction, as well as the need to rapidly and inexpensively regenerate combat capabilities. At the same time, the absence of sanctuaries in modern operational scenarios, characterised by pervasive ISR capabilities and by effectors capable of striking at great distances even in the depths of the allied apparatus, leads to perplexity over the inherent need for large, fixed airbases capable of ensuring maintenance and logistics for a large, heavy fighter such as that profiled in the sixth generation. In addition, the air fleets of peer and near-peer competitors, although equipped with high-performance aircraft, even a significant number of the fifth-generation fighters, do not represent a transformational challenge, but also appear to be counterable through circumstantial improvements in the segments of long-range air-to-air vectors, electronic warfare and MUM-T. These observations create the basis for the careful calibration of the characteristics and capabilities that will mark the next air superiority fighter, which in any case will have to succeed the current fourth and half and fifth generation fleets and motivate the not marginal time dilations in conceptualisation and design, as well as the variability of designs.

The sixth-generation programmes, in addition to fostering significant technical-engineering maturity, have, above all, so far enabled the definition of certain transformative requirements external to the individual air superiority fighter, and have promoted a significant updating of the JSF's potential employment profiles. The integration of CCAs into the ACE concept and the conduct of distributed air operations in a non-permissive hostile environment has in fact revolutionised the employment profiles of the military air tool, prioritising a scalable mass of collaborative drones with diversified payloads, aimed at manoeuvring within the adversary's zone of engagement to deploy kinetic and non-kinetic effects, coordinated by an aircraft outside the enemy A2/AD bubble. The increasing complexity of coordinating a swarm of UAVs and UCAVs in a dynamic multi-domain environment, while maintaining at least human-on-the-loop control, also calls for a possible revision of the requirements for the aircraft intended for this function. Despite the fact that the optionally manned concept aims to relieve the pilot of the task of manoeuvring the attitude directly, being able to concentrate on the evolution of the tactical situation in the air and on the ground, it cannot be ruled out that two-seater aircraft can provide a more functional, and potentially ready-to-use, combination in the case of the USAF with the F-15EX Eagle II. The experimentation of CCAs also in air-to-air combat, with the prospect that the very first wingman drones could act as missile carriers such as the AIM-120 Advanced Medium-Range Air-to-Air Missile (AMRAAM), with the task of closing in on the most advanced adversary aircraft and saturating their defences, further emphasises how collaborative drones could redefine the operational requirements in the future of the air domain.

The rapid development of CCAs, combined with the post-production technological maturation of the JSF also appears to signal that the first manifestations of the essence of the sixth generation, i.e. the integration of external autonomous systems operating synergistically with the manned aircraft, could materialise with the F-35. In fact, the USAF's own ongoing review of the NGAD programme and the first concepts of a limited capacitive package version of the same appear to point towards a progressive development, which could involve the realisation of an intermediate generation (generation 5.5 or 'fifth and a half') based on a selected optimisation of some of Lockheed Martin's aircraft characteristics for long-range collaborative combat.

Regardless of the divergence of trajectories, the obsolescence of Western countries' air fleets, the immanence of strategic competition and the transformation of the air battlefield impose the need to update the military air instrument by overhauling its doctrines, capabilities and employment profiles. The sixth-generation system of systems, whatever its practical articulation will be in the future, will represent in this perspective the inevitable epicentre of the future of the air domain.

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