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- HAVE DRONES OVERTAKEN THE OFFENSIVE ADVANTAGE OF 5TH GENENERATION STEALTH FIGHETR JETS? -

- Security Studies: from Terrorism to Peacekeeping -

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1. Introduction

1.1 Introduction

Theories on offense and defense are one of the most notorious and discussed topics by international relations and security studies researchers[1]. Addressing when states are more vulnerable to conquest, or more likely to attack another one, may produce exponential consequences on global politics and in terms of distribution of power[2]. Nonetheless, it is important to remark that most of the literature presents different opinions when appointing the impact of the development of military technologies on this balance[3]. Cyber-attacks, electronic warfare, stealth capabilities and in particular a wide disposition of Unmanned Autonomous Combat Vehicles (UCAVs), may indeed have a deep impact on offense/defense principles and so on the battlefield[4]. Unmanned aerial vehicles (UAVs), or generally called "drones", have become one of the main feature of modern conflicts[5] and had researchers scratching their heads about what will be their peak potential in the near future[6]. The literature is still trying to fully address the complete consequences of a wide armed drones deployment in conflicts, as well as identifying the actors that could positively rely on them[7]. Some researchers believe that UAVs and UCAVs will cause a military revolution, unleashing regional and international

[1] Michael E. Brown, Owen R. Coté Jr., Sean M. Lynn-Jones, and Steve E. Miller, "Offense, Defense, and War", MIT Press, 2004

[2] George H. Quester, "Offense and Defense in the International System", John Wiley & Sons, 1977

[3] Jack S. Levy, "The Offensive/Defensive Balance of Military Technology: A Theoretical and Historical Analysis", International Studies Quarterly, 1984

[4] Andreas Lorenz, Messengers of Death: are Drones Creating a New Global Arms Race?", Der Spiegel, 2011

[5] Christopher Coker, "Warrior Geeks: How 21st Century Technology is Changing the Way We Fight and Think about War", London: Hurst, 2013

[6] Stephen Bryen, "Armed Drones Revolutionizing the Future of War", Asia Times, 2020, asiatimes.com/2020/12/armed-drones-revolutionizing-the-future-of-war/

[7] Antonio Calcara, Andrea Gilli, Mauro GIlli, Raffaele Marchetti, Ivan Zaccagnini, "The Drone Revolution in Military Affairs? Understanding the Hider-Finder Competition in Air Warfare", International Security Volume 46, Issue 4, MIT Press, 2022

instability while making the deployment of troops on the ground obsolete[8]. Other experts, instead, suggest that only already powerful actors can properly rely on and develop drone-technologies, so that their impact is expected to be less meaningful both for military strategies and for global stability[9]. Generally, we can affirm that the influences of drone technology on the offense-defense balance theory is still pretty unclear, while their offensive matrix appears to be more predominant according to classic offensive-theories principles[10].

The tragic 2022 Russia-Ukraine war is providing many interesting opportunity to observe the deployment (and effectiveness) of drones in the air domain[11]. First of all, the Unmanned Combat Air Vehicle (UCAV) Bayraktar TB-2 by Baykar, a Turkish tech manufacturer, stands strong as one of the main protagonists of the conflict. TB2s have been previously used in the 2019 Libyan civil war[12], as well as in some counterterrorism operations across Turkey's border in Syria and Iraq[13], showing some truly remarkable capabilities of taking down enemy infantry and armored vehicles as well[14]. With an estimated cost between one and two million US dollars per unit[15] this drone possesses a peculiar shape made by a flat framework with inverted V-tail structure, angled wings and a rear propeller. It has an operative flying altitude window between 3 and 7 kilometers and is made mainly of light materials such as carbon fiber and aluminum. Equipped with laser-guided smart ammunition,

[8] Michael J. Boyle, "The Drone Age: How Drone Technology Will Change War and Peace", Oxford: Oxford University Press, 2020

[9] Antonio Calcara, Andrea Gilli, Mauro GIlli, Raffaele Marchetti, Ivan Zaccagnini, "The Drone Revolution in Military Affairs? Understanding the Hider-Finder Competition in Air Warfare", International Security Volume 46, Issue 4, MIT Press, 2022

[10] Michael Mayer, "The New Killer Drones: Understanding The Strategic Implications of Next-Generation Unmanned Combat Aerial Vehicles", International Affairs, Vol. 91, 2015

[11] Heiko Borchet, Torben Schutz, Joseph Verbovsky, "Beware the Hype. What Military Conflicts in Ukraine, Syria, Libya and Nagorno-Karabakh (Don't) Tell Us About The Future Warfare", ResearchGate, 2021

[12] Franz-Stefan Gady, " Useful, but Not Decisive: UAVs in Libya's Civil War" International Institute for Strategic Studies, 2019

[13] Dan Gettinger, "Drones Operating in Syria and Iraq", Annandale-on-Hudson, N.Y.: Center for The Study of the Drone, 2016

[14] Christopher Phillis, "The Battle for Syria: International Rivalry in the New Middle East", Conn.: Yale University Press, 2016

[15] Paul Iddion, "Why Iraq Would Want to Buy Turkish Drones and Attack Helicopters", Forbes, 2021, forbes.com/sites/pauliddon/2021/08/29/why-iraq-would-be-interested-in-turkish-drones-and-attack-helicopters/?sh=1f3127b73d0b

this UCAV is controlled and monitored remotely via a ground operation station, where the aircrew can command movements and weapons deployment of the machine[16]. The TB2 has proven to grant tactical superiority when facing Russian anti-aircraft systems and tanks[17], quickly acquiring considerable notoriety also to the world-wide popular public[18]. Due to its compact dimensions, reduced heat trail and low-slow-fly (LSF) feature, is apparently very hard for radars to track a TB2 while operating in midair, making it also, as a consequence, exceptionally concealed against enemy ground-fire[19]. Publicity presented by Ukrainian propaganda on Twitter showed drone-captured videos of TB2s destroying Russian missiles batteries while intercepting, and then blocking, enemy's supply lines by bombing transport trucks[20]. However, in the last months, these kind of video-clips have not been published as frequently as before, showing that Russian forces may have finally caught up[21]. Whatever the case, the impact of the TB2s in the war has been more than positive according to Oleksii Reznikov. The Ukrainian Defense Minister claimed indeed that "they [TB2s] have shown themselves very successfully in battle"[22], describing how the drone's precise strikes have allegedly contributed to level the gap in fire power between Ukrainian's resistance and Russia, especially during the early stages of the operation. Other purchases of TB2 units are expected to be bought soon by Kiev's resistance[23].

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16 BaykarTech.com/en/bayraktar-tb2

17 Nailia Bagirova, "After Ukraine, 'whole world' is a customer for Turkish drone, maker says", Reuters, 2022, reuters.com/business/aerospace-defense/exclusive-after-ukraine-whole-world-is-customer-turkish-drone-maker-says-2022-05-30/

18 Kimberly Johnson, Meg Godlewski, "Turkish Bayraktar Drone Inspires Son of Ukrainian Resistance", Flyingmag.com, 2022, flyingmag.com/turkish-bayraktar-drone-inspires-song-of-ukrainian-resistance/

19 H.I. Sutton, "Incredible Success of Ukraine's Bayraktar TB2: The Ghost Of Snake Island", NavalNews, 2022, navalnews.com/naval-news/2022/05/surprising-success-of-ukraines-bayraktar-tb2-the-ghost-of-snake-island/

20 Twitter.com/DefenseU

21 Stephen Witt, "The Turkish Drone That Changed The Nature of Warfare", TheNewYorker, 2022, newyorker.com/magazine/2022/05/16/the-turkish-drone-that-changed-the-nature-of-warfare

22 Ragip Solyu, "Ukraine Received 50 Turkish Bayraktar TB2s Drones Since Russian Invasion", Middle East Eye, 2022, middleeasteye.net/news/russia-ukraine-war-tb2-bayraktar-drones-fifty-received

23 David Hambling, "New Turkish Bayraktar Drones Still Seem To Be Reaching Ukraine", Forbes, 2022, forbes.com/sites/davidhambling/2022/05/10/new-turkish-bayraktar-drones-still-seem-to-be-reaching-ukraine/?sh=4eb4528e685b

Another interesting insight provided by the ongoing conflict is the performance of the Russian Air Force. In fact, despite the odds, Ukrainians were able to successfully deny air superiority to their enemies up to these days[24]. Believed to be a necessary prerequisite to achieve success of operations and campaigns[25], Air University's Doctrine defines air superiority as "that degree of control of the air by one force that permits the conduct of its operations at a given time and place without prohibitive interference from air and missile threats"[26], a target that Russia's army definitely has not achieved yet. It is very difficult to scientifically address the causes of the underperformance carried on by the VVS RF during the early stages of the conflict. On paper, Russia had all the possibilities to rapidly settle its dominion over Ukraine's skies and grant itself the tactical benefit of such an important achievement. So, what exactly went wrong? The biggest problem seems to be of doctrinal and technological nature. According to some, Russia's failure to take down enemy's air power can be attributed to a lack of organization and operational-level incompetency, furtherly worsened by a low average flight time of pilots[27]. Russian air force, moreover, was never configured to provide ample ground strikes to support its own military: striking behind the enemy lines is something that the Russian air force is specially ill-equipped to do. The first and foremost role of Russia's air force has always been air combat, where the goal is to try and keep enemy aircrafts away especially over Russian-owned territory, where layered sensor networks exist, improving the fleet's battle effectiveness. These lacks, merged with doctrinal inadequacy, had heavy consequences: on the 13th of May 2022, Ukraine claimed the takedown of 200 enemy aircraft[28] and, as the conflict continues, we still witness the absence of large-scale Russian air operations[29]. NATO's AEW&C (Airborne Early

[24] Philips Payson O'Brien, Edward Stringer, "The Overlooked Reason Russia's Invasion is Floundering", The Atlantic, 2022, theatlantic.com/ideas/archive/2022/05/russian-military-air-force-failure-ukraine/629803/

[25] School of Advanced Airpower Studies, "The Evolution of Airpower Theory", Air University Press, 1997

[26] Air University, "Doctrine Advisory: Control of the Air", 2017

[27] Harry Boneham, "Russia's Struggle to Establish Air Superiority in Ukraine", GlobalData, Army Technology, 2022, army-technology.com/comment/air-superiority-in-ukraine/

[28] Facebook.com/president.gov.ua/videos/417501393181766/

[29] Christopher Woody, "Top USA Air Force General Says the Russian Air Force's Struggles in Ukraine are Surprising Because Russia is Fighting its 'Own Systems'", Business Insider, 2022, businessinsider.in/international/news/the-

Warning and Control) aircrafts are playing a huge role as well, favoring Ukrainians' defense. Patrolling over the western skies, AEW&Cs can in fact warn the resistance promptly when an air incursion takes place.

Currently forced to fly on extremely-low altitudes in order to avoid long-range Surface to Air Missiles (SAMs)[30] in the eastern borders of the conflict, Russian jets and helicopters are now exposing themselves to USA-made Javelin missiles carried on by Ukrainian infantry[31]: this resulted in an evident decline of Russian incursions. Having stated that, it is important to underline how the deployment of Russia's 5th generation stealth fighter jet, the Sukhoi Su-57, remains not confirmable by current available information[32]. As a multirole 5th generation stealth fighter jet, the Su-57 represent the peak of Russia's air performance, stealth technology and fire lethality[33]: logically, it would make up for a perfect addition to the Federation's armed forces involved in the war. The reasons about why it has not been brought into action yet are unclear and could be multiple. We could speculate that Russian commanders decided to keep the Su-57 for deterrence purposes only[34], while some leakages presented by journalists would instead suggest a delay in the development of the project[35], making the Su-57 *de facto* not ready for actual medium and high combat intensity. Or maybe, it could be that Russians have suddenly realized how ineffective stealth fighters jets have become in comparison with

russian-air-forces-struggles-in-ukraine-are-surprising-because-theyre-fighting-their-own-systems-top-us-air-force-general-says/articleshow/92398335.cms

30 David Axe, "Russian Jets Are Flying So Low To Dodge Ukrainian Air-Defense That They're Running Into The Ground", Forbes, 2022, forbes.com/sites/davidaxe/2022/06/24/russian-jets-are-flying-so-low-to-dodge-ukrainian-air-defenses-that-theyre-running-into-the-ground/?sh=22b72021a251

31 Maximilian K. Brember, Kelly A. Grieco, "In Denial About Denial: Why Ukraine's Air Success Should Worry the West", WarOnTheRocks, 2022, warontherocks.com/2022/06/in-denial-about-denial-why-ukraines-air-success-should-worry-the-west/

32 Brent M. Eastwood, "Russia's much-touted Su-57 stealth fighter jet doesn't appear to be showing up in Ukraine", Business Insider, 2022, businessinsider.com/su57-why-russia-wont-send-new-stealth-fighter-to-ukraine-2022-6?r=US&IR=T

33 TASS, "Russia's Su-57 Outshines US Fifth-Generation Fighters, Says Expert", Russian News Agency, 2021, tass.com/defense/1352447

34 Kris Osborn, "Russian Su-57 Fighter Jets Overmatched Against US and NATO F-35 Firepower", Warrior Maven, Center for Military Modernization, 2022, warriormaven.com/russia-ukraine/russian-su-57-f-35-nato

35 Wesley Culp, "Russia Only Has 10 Su-57 'Felon' Stealth Fighters", 19fortyfive.com/2022/06/russia-only-has-10-su-57-felon-stealth-fighters, 2022

the latest technologies, and even the mightiest of them at their disposition will not be able to provide and secure enough tactical advantages to turn the odds of the conflict in their favor, securing Russian control over Kiev's sky. Whatever the eventuality, we do not know if, or when, the Su-57 will be deployed against Ukraine[36].

What instead appears to be clearer, at least at first sight, is that the Russia-Ukraine conflict may become witness to an historical turning point. On one hand, in fact, we see drone technologies overtaking the war scenario with remarkable combat performances and relatively low cost production; on the other hand, we witness the complete failure of traditional fighter jets in assessing their air dominance against an outnumbered enemy, unable to face and overcome Ukraine's Anti Access Area Denial (A2/AD) capabilities when enhanced by NATO's equipment. This is what the research will try to understand and explore further. In order to be more complete and rounded about the feasible capabilities of the two parts, only 5th generation stealth fighter jets will be taken into consideration. These aircraft, in fact, developed through decades-long projects, represent the zenith of military performance involving a direct human interaction[37]; drones, on the contrary, draw the line of a more modern approach to the conflict, exploiting the latest technologies in order to avoid on-ground human presence[38]. Will all of this affect century-long offensive-defensive dogmas and strategies? Are drones inherently superior to stealth fighter jets in terms of offensive capabilities? Are the wonders that only modern aircrafts can achieve still valuable for military assets? Have drones overtaken the offensive advantage of 5th generation stealth fighter jets?

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[36] Thomas Newdick, "Let's Talk About The Rumors That Russia's Su-57 Is Participating In The War In Ukraine", The WarZone.com/lets-talk-about-the-rumors-that-russias-su-57-is-participating-in-the-war-in-ukraine

[37] Jeffrey W. Hamstra, "The F-35 Lighting II: From Concept to Cockpit", Amer Institute of Aeronautics, 2019

[38] Tim Hsia and Jared Sperli, "How Cyber Warfare and Drones Have Revolutionized Warfare", At War blog, New York Times, 2013, nytimes.com/atwar.blogs.nytimes.com/2013/06/17/how-cyberwarfare-and-drones-have-revolutionized-warfare/

1.2 Offensive and Defensive Balance: Overview

Before addressing the competition between stealth fighter jets and drones over offensive advantages and capabilities, it is remarkable to provide a general overview about offense-defense theory and, in particular, the concept of balance between the two.

Offense-defense theory continues to appeal scholars because it offers a compelling argument for why intense security competition among states is not a consequence of the structure of international system[39]. Quoting Rebecca Slayton, "State perceptions that technology favors the offense increase fears of attack, encourage arms races, and through interactions between fear and capabilities, increase the likelihood and consequences of war"[40]. The idea that some technologies can make offense or defense easier dates back, at least, to the League of Nations discussion on reducing/limiting weaponry, back in the 1930s[41]. Therefore, the formalization of offense-defense theory came much later[42]. According to it, relevant technological changes shift the balance in favor of the attacker, who should technically have more possibilities to win quick and decisive victories[43]. In a 1997 publication by *The Economist*, it is proclaimed that a military revolution will be coming in the following years, which is now our contemporaneity, where offense will strengthen relatively to defense, creating "a strong incentive to strike first"[44]: this is known as "first-strike advantage". To furtherly prove this point, researcher Karen Ruth Adams adds that "in offensive-dominant eras, security should come from attacking first; instead of declaring war, states should engage in surprise attacks […] and attacks should frequently result in conquest". It is estimated that offense-dominant eras were from 1800 to 1849, and once again from 1934 to 1945 with the Second World War: this was possible due to the

[39] Keir A. Lieber, "Grasping The Technological Peace", Harvard College and Massachusetts Institute of Technology, International Security Vol.25, 2000

[40] Rebecca Slayton, "What Is the Cyber Offense-Defense Balance?", International Security Vol.41, MIT Press, 2016

[41] Robert Jervis, "Cooperation Under The Security Dilemma", World Politics Vol.30, Princeton University Press, 1978

[42] George H. Quester, "Offense and Defense In the International System", Routledge, 2002

[43] Keir A. Lieber, "Grasping The Technological Peace", Harvard College and Massachusetts Institute of Technology, International Security Vol.25, 2000

[44] "Select Enemy. Delete", The Economist, March 1997, economist.com/special/1997/03/06/select-enemy-delete

technological environment of the time, that allowed for effective attacking approaches rather than defending[45]. An advanced technology may be expected to provide absolute gains in terms of offensive capabilities but, as researchers Drew Herrick and Trey Herr explain, complex technologies can also pose different challenges for the attacker[46]: the fact that complexity gives the offensive advantage is just purely probabilistic[47]. Van Evera, moreover, points out how a strict focus on offense may indeed be extremely dangerous for world peace. In his paper *The Cult of Offense and the Origins of First World War*, the American researcher suggests how the beginning of the First World War had actually deep roots in a predominant offense-focused environment, that consequently led to Germany starting the War in 1914. Nonetheless, many other states such as the United Kingdom, France and Russia were developing similar attack and conquest strategies, all aimed to strike in specific "windows" of opportunity, while almost completely rejecting defensive approaches because of moral-centered and idealistic reasons[48]. At that times, as Van Evera shows, offense dogmas were blurred with mythical or mystical arguments that completely obscured the technical dominion of the defense[49]: all of this resulted in a common belief of easy conquest, overtaking not only the military domain but international politics as well[50]. Is in fact in these years that we witness the widespread application of Darwinist principles of survival to the states' dimension, which implied a furious competition among each-others that would have ended only with the triumph of the strongest and the doom of the weak: a common image which assumed, indeed, a powerful offense rather than a well-planned defense[51].

[45] Karen R. Adams, "Attack and Conquer", Harvard College and Massachusetts Institute of Technology, International Security Vol.28, 2003

[46] Rebecca Slayton, "What Is the Cyber Offense-Defense Balance?", International Security Vol.41, MIT Press, 2016

[47] Drew Herrick, Trey Herr, "Combating Complexity: Offensive Cyber Capabilities and Integrated WarFighting", George Washington University and Harvard University, 2016

[48] Van Evera, "The Cult of Offensive and the Origins of the First World War", International Security Vol.9, MIT Press, 1984

[49] Captain George Gilbert, quoted in Snyder, "Defending the Offensive"

[50] Joachim Remark, "The Origins of World War I, 1872-1914", Hinsdale, III: Dryden Press, 1967

[51] Barbara Tuchman, "The Guns of August", New York: Random House, 1938

Having presented the concept of offense, it is time to stress out defense[52]. Before the nuclear revolution, it was believed that explosives technology were neutral, because they granted similar capabilities that both the attacker and the defender could have exploited. What made the difference was how these fire innovations were deployed on battlefields, in order to achieve a better mobility or more firepower, rather than their technology itself. However, after 1945, defense theories, dogmas and strategies have all been overcome by what many consider to be the ultimate defensive technology: nuclear weapons. A-bombs, in fact, with their virtually unlimited firepower, rewrite the foundation of defensive theories and weapons, making the offensive conquest impossible, or even pointless, under a wide range of circumstances. This is why researchers that explore possible military clashes, such as Steven Biddle, tend to underline how their works often do not consider the awful possibility of a nuclear retaliation. A state-actor would have no reasons to conquer any land if its opponent can make that same land unsuitable for human-life and activities. Quoting the paper *Attack and Conquer?,* nuclear weapons would "greatly increase the costs states might have to pay for attacking others' territory or vital interests". So, from here, comes also the concept of deterrence, given the fact that any kind of aggression against an actor with nuclear capabilities could be punished through a nuclear response: the cost for such behavior or action becomes immediately unsustainable. As expert Karen Ruth Adams presents, however, deterrence and defense are two separated concepts. Deterrence "means discouraging the enemy from taking military actions by posing him a prospect of cost and risk outweighing his prospective gains", while defense means "reducing our own perspective costs and risks in the event that deterrence fails"[53]. Since humankind is now capable of developing nuclear weapons with relative ease and low costs[54] deterrence operations have become dominant compared

[52] For classical strategic thought, see Peter Paret, Gordon A. Craig and Felic Gilbert, "Makers of Modern Strategy: From Machiavelli to Nuclear Age", Princeton University Press, 1986; Michael I. Handel, "Masters of War", Routledge, 2001

[53] Karen R. Adams, "Attack and Conquer", Harvard College and Massachusetts Institute of Technology, International Security Vol.28, 2003

[54] Elliott Negin, Lisbeth Gronlund, "How Much Does it Cost to Create a Single Nuclear Weapon?", TheEquation.com, 2013, ucsusa.org/elliott-negin/how-much-cost-to-create-nuclear-weapon/

to offensive and defensive ones. Deterrent operations are actions in which a state prepares to use force, or where a state wants to show off its abilities in using force trough attacking another state's non-military assets in order to deter that same state from attacking[55].

So, starting from 1946, we can say that our world is experiencing a deterrence dominant balance even to present days. Offense-defense balance, generally, provides a systematic method of forecasting when the balance of power is threatening and when it is not. Considering what was written previously, it appears that our world has not experienced yet an overall revolution in this balance. Big powers, such as the winners of the Second World War, still grant offensive capabilities due to their arsenals and weaponry, while the nuclear potency of some states provides the needed deterrence that shapes the distribution of power around the globe exploiting the principle of Mutual Assured Destruction. Because of that, none of those great powers was able to conquer or attack another one after 1946: the current technological environment, merged with the prospect of total annihilation, does not allow so.

Nonetheless, it is still important to stress how drones and fighter jets fit in this delicate equilibrium, what are the outcomes of their technology for the actors that rely on them, or if one of the two is going to overtake the other in terms of offensive advantage in the upcoming decades.

1.3 Aim of the Research and How to Evaluate Offensive Advantage

This paper explores if drone technology has the stakes to put in question the offensive advantages granted by last generation fighter jets, hoping to present a better understanding about the supposed drone revolution taking place in military affairs as well. Drones, in fact, represent an appealing alternative for a wide window of employment, including the gaining air supremacy, and their reduced costs in terms of both resources[56] and human lives are of growing interest for nations as well as for

[55] Glenn H. Snyder, "Deterrence and Defense", Princeton University Press, 1961

[56] Reduced costs if compared to fifth generation fighters' ones. Nonetheless, just like how this paper will explain furtherly, drones' requirements needed for both operating as well as manufacturing them may still represent huge entry-barriers that most countries will never be able to overcome.

military alliances. Skies have always been one of the most challenging as well as lethal environments where to execute war and drones seem to possess some features that may erode the overall supremacy that only extremely expensive 5th generation stealth fighters currently own. It will be of crucial interest trying to understand where drones fit in the current run for aerial supremacy and, being a relatively new technology, the blueprint for their future strategic and combat roles are yet to be fully understood.

In order to confront and evaluate the offensive advantage possessed by the two technologies, a deep analysis about stealth shall be presented first, being perhaps one of the most revolutionary features that changed forever air warfare as it is intended today. Stealth is indeed required for contemporary and for future battle scenarios as well. Then, the paper will introduce different countermeasures for stealthy air vehicles that have been developed over the years, including technologies that possibly hold the capability to deny, even partially, the overwhelming advantages granted by stealth capabilities. The following chapters will be instead destined to a wider presentation of both stealth fighter jets, in particular 5th generation ones, as well as drones and their supposed revolutionary role in the current military affairs. Such chapters will help to evaluate not only technological features and capabilities but also economic and industrial aspects of the scrutinized technologies. In fact these elements, despite not being strictly related to combat or strategic deployment, help to grasp a more complete understanding of the challenges and barriers that drones and fighter jets present to the nations that have interest in operating and building them. Lastly, a comparison between the two will occur, where the key variable will be chances that enemies have to locate the intruder over their airspace. In fact, stealth, being not an all-or-nothing technology, is determined by some crucial variables that will translate into a better or a worse concealment from nemy sensors. With such comparison, we should be able to acknowledge which technology possesses the best capabilities to grasp the maximum chances to carry on and conclude the mission successfully. The freedom that stealth manned and unmanned vehicles can grant to themselves while operating

over enemy's skies would make up for a perfect parameter to empirically understand offensive advantage and if one of the two has superseded the other in such a term. Of course, different parameters beyond stealth will be considered as well and the winner will be the one to achieve best chances of radar concealment, reachable operative area, possibility to survive an engagement and so on. The F-35 will be the one to represent 5th generation fighters' capabilities, given the enormous amount of literature available which also reflect its crucial role for western air power in the years to come. The MQ-9 Reaper, considered by experts to be the most advanced and lethal drone currently in full operational status, will help the research to assess contemporary drones' capabilities.

2. Stealth

2.1 Introduction to Stealth

Stealth technology is a sub-discipline of military tactics, exploiting active and passive tools for the sake of making vehicles and weapon systems less visible to detection methods and instruments[57]. In the late 1980s, the word "stealth" experienced a sudden peak in popularity. American media, in fact, reported that a significant part of the national defense budget was destined towards the development of the so-called "stealth technologies"[58]. The interest aroused about the topic was significant. However there were, and there are, numerous misconceptions regarding stealth. Media, in fact, presented to the public the tricky idea that newer aircrafts, shaped with a stealth design, would have been magically invisible to those same radars that previously were able to detect earlier generation aircrafts. The audience, despite being given some superficial and ambiguous information, quickly understood that the implications provided by the successful development of this technology were massive: in one single shot, stealth tech could have made obsolete the whole defense system of enemies, and in particular Soviet Union's, giving a predominant strategic advantage to the USA[59]. Because of that, stealth development and tests were actually carried on in absolute secrecy since 1958[60].

It is fundamental to remark that stealth does not mean being completely invisible in absolute terms: it means to be exceptionally concealed to your foe's eyes, forcing it to face an elusive but still deadly target. Stealth works by blurring the chain-procedures that come when facing an enemy aircraft, a

[57] G. A. Rao and S. P. Mahulikar, "Integrated review of stealth technology and its role in airpower", The Aeronautical Journal, volume 106, Cambridge University Press, 2002

[58] John T. Corell, "History of Stealth: From Out of the Shadows", Air Force Magazine, 2019, airforcemag.com/article/history-of-stealth-from-out-of-the-shadows/

[59] Ben R. Rich and Leo Janos, "Skunk Works", Little, Brown and Company, 1994

[60] Gene Poteat, "Stealth, Countermeasures, and ELINT, 1960-1975", Studies in Intelligence 48, US Central Intelligence Agency, 2013

challenging objective to achieve even with nowadays capabilities[61]. In particular, the duel between attackers and defenders is divided into three main phases: detection, engagement and probability of kill. At first we have the detection phase, which consists in the task of spotting and tracking the approaching enemy aircraft. Then, there is a second phase where the engagement takes place: defending fighters can be sent and start a dogfighting against the intruders, or ground-based defenders can track and aim at the enemy with their A2/AD (Anti-Access Area-Denial) system. Lastly, we have the probability of kill. Probability of kill involves a number of factors; in its simplest form it assumes the aircraft is hit, but the chance of destroying the vehicle depends on the nature and extent of the damage sustained. In brief, quoting American security analyst Rebecca Grant, "it takes a chain of detections, interpretations, and correct actions by defenders to intercept an aircraft; stealth breaks up the chain by removing, reducing or obfuscating a significant percentage of those opportunities"[62].

Stealth design principles can be integrated not only into aircrafts but into ships, satellites, missiles, buildings and unmanned piloted vehicles too[63]. Merriam-Webster dictionary defines stealth as "the act of going furtively or as a secret procedure or action"; stealthy, furthermore, is defined as "accomplished secretly or furtively or acting clandestinely, furtive, or sly"[64]. Achieving an important degree of concealment in military operations is a huge deal, because it provides important benefits and advantages for the actor using it. First, a vehicle with stealth features is capable of pursuing its mission with a lower enemy's interference, gaining advantages in how close it can get to the opponent's air defense systems or targets. Avoiding the enemy's intervention means that the resources destined to that mission will be reduced as well, since attrition and losses are now statistically less likely to happen. These advantages also are translated into more contained mission's costs and more security for the pilots operating. Lastly, stealth capabilities pave the way for new kinds of operations

[61] Rebecca Grant, "The Radar Game", Mitchell Institute, 2010
[62] Rebecca Grant, "The Radar Game", Mitchell Institute, 2010
[63] G.A. Rao and S.P. Mahulikar, "Integrated review of stealth technology and its role in airpower", Cambridge University Press, 2016
[64] Merriam-Webster.com

that previously would have been impossible to carry out. Quoting once again Rebecca Grant, "already there are regions of the world where only stealth aircrafts can operate with a good chance of completing the mission", probably hinting at the Western Pacific environment, where the military competition between China and USA is expected to peak in the upcoming years[65]. Overall, in the military domain, stealth entails a greater chance of survivability, defined as "the ability of aircraft and aircrew to accomplish the mission and return home". Nonetheless there are, and there have been, also different methods to undo the adversary's advantage, "either by low-level ingress, high-altitude operations, speed, electronic countermeasures or, indeed, stealth", quoting the book *The Radar Game*. However, of all these ways, the ability to diminish the effects of radar return, so being stealthy, is still one of the most challenging, but perhaps one of the most rewarding[66].

As previously introduced, stealth design can fit in almost any kind of weapon system. Nonetheless, it grants the most benefits to vehicles that, when spotted by the enemy, face poor means of defense: fighter jets and strategic bombers are the best examples. The air domain, in fact, provides little, if not zero, possibility of natural concealment or protection for vehicles and pilots[67]. Moreover, as technology has progressed, speed alone is no longer enough to overtake missiles' and defense systems' threat and, consequently, stealth features have become an intrinsic necessary feature for modern and future war aircrafts[68]. Combat experience has already proved the importance of incorporating stealth properties into air vehicles: in the 1999 NATO air-war with Serbia, B-2 bombers flew missions in heavily guarded airspace but still successfully achieved their missions (from attacking the Novi Sad bridge to destroying batteries of surface-to-air missiles)[69]; in the intensive air

[65] Steven Biddle and Ivan Oelrich, "Future Warfare in the Western Pacific", International Security Vol.41, MIT Press, 2016

[66] Rebecca Grant, "The Radar Game", Mitchell Institute, 2010

[67] John Shaeffer, "Understanding Stealth", Marietta Scientific, 2018

[68] Gp. Cap. Joseph Noronha, "Countering Stealth Aircraft Technology: The Race to See Through 'Invisibility'", Indian Defense Review, 2018, indiandefencereview.com/news/countering-stealth-aircraft-technology-the-race-to-see-through-invisibility/

[69] John A. Tirpak, "With Stealth in the Balkans", Air Force Magazine, 1999, airforcemag.com/article/1099stealth/; Daniel L. Haulman, "The U.S. Air Force in the Air War Over Serbia, 1999", Air Power History Vol.62 No.2, 2015

war with Iraq, during the early 2003, we saw the use of B-2s and F-117 against different kinds of targets around Baghdad[70].

In spite of the potential brought to air fleets, stealth has faced different critics by public opinion and policy makers. Due to the high costs of production and maintenance, stealth aircrafts have been protagonists of different budget-cuts as well as canceled programs, despite it is widely acknowledged how their high price-tag paid back the investment up to this point. However, stealth still is one of the main pillars building the core of the future American Air Force. The USA has nowadays the most reduced air fleet since 1991 and the survivability granted by stealth has become more crucial than ever for the future of American airpower. The Joint Strike Fighter F-35 jet[71] remains the nation's single biggest bet for defending its dominion over skies in the upcoming decades, planning to supersede all the F-16s with more than 1'000 units[72]. The overall goal is indeed to replace previous generations of bombers and fighter jets with their newer stealthier counterparts, preferring quality of vehicles over their quantity, gaining strategic advantages but also cost reduction benefits. Moreover, previous models of jets face fewer chances to positively operate in a context of perduring warfare and their lack of stealth capabilities is one of the most deadly vulnerabilities. As quoted in the book *Survivability in the Digital Age: The Imperative For Stealth*, "airpower is an equipment -intensive form of military power; without aircraft, a state does not possess airpower"[73]. So, stealth clearly appears to be the most versatile solution to bet on, being up to accomplish the best possible

[70] Dario Leone, "The Story of the F-117 Nighthawk Airstrikes Over Baghdad That Marked The Beginning of Operation Iraqi Freedom", The Aviation Geek Club, 2017, theaviationgeekclub.com/story-f-117-nighthawk-airstrikes-baghdad-marked-beginning-operation-iraqi-freedom/

[71] For a wider picture of the Joint Strike Fighter F-35, see Fabrizio Coticchia, "A Controversial Warplane: Narratives, Counternarratives and the Italian Debate on the F-35", Alternatives: Global, Local, Political, Vol. 41, Sage Publications, 2016; Alessandro Marrone, "Italy and the F-35: Rationales and Costs", International Journal, Vol. 68, 2013

[72] Valerie Insinna, "How Many F-35 does the Air Force need?", Defense News, 2021, defensenews.com/digital-show-dailies/air-force-association/2021/09/07/new-us-air-force-study-asks-whats-the-right-number-of-f-35s/; Rebecca Grant, "The Radar Game", Mitchell Institute, 2010

[73] Maj. Gen. Mark Barrett and Col. Mace Carpenter, "Survivability in the Digital Age: The Imperative For Stealth", Mitchell Institute, 2017

capabilities in the air domain concerning offense, defense and, most importantly, survivability against the newest anti-aircraft detection and strike technologies for the upcoming decades.

2.2 Stealth: History and Evolution

Stealth was born as a response to the use of radars. The predominant defensive advantages provided by radar's technology forced the pursuit for the development of new methods to trick radio waves with the goal of obfuscating radar's awareness[74]. How radars work and their technology will be described more in detail in chapter 2.3 and chapter 3.2; here, I will present a brief description about how stealth evolved through time in the air domain, in order to better understand the circumstances that led to its emergence and its consequences in the battlefields. During World War I, the only way to detect an incoming war plane was just with mere human eyes: this resulted in defenders struggling to gain early warning against an air attack. After the warning was given by the troops, reports were relayed through telephones to the airfields, where commanders launched airplanes to intercept the attackers as fast as they could. Once the aviator could see its opponent, both were limited by the tracking capabilities of the human eye, making the element of surprise predominant in order to win air clashes. Because of that, airplanes usually tried to fly among clouds or to attack out of the sun, so that they could grasp the best surprise effect possible[75]. However, even for the years to come, the best solution to grant maximum concealment was operating at night: the cloak of darkness allowed in fact for almost complete cover, while looking for supply depots and railroads to targe. During the First World War, the most part of air operations did not face well-organized antiaircraft guns or defenses and pilots often felt like they had a massive upper hand against ground fire[76]. In those same years, we also witnessed the general drift towards the development of specialized aircraft depending on the

[74] Col. Neil G. Kacena, "Stealth: An Example of Technology's Role in the American Way of War", Air War College, Air University, 1995
[75] Rebecca Grant, "The Radar Game", Mitchell Institute, 2010
[76] Lee B. Kennet, "The First Air War, 1914-1918", New York: The Free Press, 1991

missions they were planned to conduct, in order to ensure maximum battle effectiveness[77]. During the interwar age, the doctrine of airplane spotting remained pretty much the same of 1918: it was still considered impossible to think of other methods to detect an aircraft different from eyes and ears. Surprise could still be achieved and could still play a relevant role in clashes, however engineers preferred to focus on features that allowed for rugged and faster airplanes, rather than developing systems to improve concealment[78].

The real revolution happened during the 1930s. As the next phase of survivability duel began, neither the aircraft nor the doctrine were ready for what was about to come. In the summer of 1938, Telefunken, a German corporation, was testing a reliable radar device. The potential of such technology was immediately understood by the Luftwaffe as Dr. Runge reports "when I explained that it could cover a 50 kilometers area, locating an aircraft despite fog and even at night, their reaction was astonishing"[79]. The use of radar, and the early warning granted by it, would have permanently denied the surprise effect, instantly crumbling the pillar of all air forces' doctrine of that time. During the Second World War, in the 1940 Battle of London, the Royal Air Force was the first to score big benefits from radar technology. In that historical clash, the RAF was capable of pushing back the attacking Luftwaffe despite being outnumbered in terms of aircrafts' quantity[80]. Exploiting radar's early warning was necessary for achieving victory: given the signal, the British managed to direct all of their fighters against the attacking formation of enemies, instead of letting them patrol assigned air defense sectors as usual. The RAF stated that radar early warning made fighters effective in a way that had not been imagined, allowing to compensate for the inferiority in numbers while providing a much better estimation of approaching German aircrafts. The Battle of London proved to be crucial for the future outcomes of the Second World War, with the amphibious invasion plan against the

[77] Alan Stephens, "The War in the Air 1914-1994", Air University Press, 2001

[78] William Mitchell, "Memoirs of World War I", New York: Random House, 1960, the memoir was first published in 1928

[79] David Pritchard, "The Radar War: Germany's Pioneering Achievement, 1904-45", Harper Collins, 1989

[80] Matthew Cooper, "The German Air Force, 1933-1945: anatomy of a Failure", New York: Jane's, 1981

United Kingdom permanently doomed to failure due the complete denial of Germans' air superiority above London's sky. As the world conflict kept going, this battle presented some clear trends that would continue to alter the duel between attackers and defenders for the years to come. Radars forced the doctrine of air fighting to rapidly evolve as the skies became one of the most deadly environments for warfare. Unable to deny radar's early warning, commanders started to deploy bombers during nighttime in order to be less visible by enemy ground fire; at the same time, the unique ability of airpower to attack strategic target (such as bridges, roads and railroads), preventing the opponent from moving troops and supplies, proved to be more and more crucial for achieving victory[81].

During the Cold War era, technology took another step forward and the strategic requirements for the air domain became even more demanding. Developments in guided missiles technology, combined with general improvement in radar detection, made the quest for air dominance even more deadly[82]. Most importantly, the need for air defenses to guard USA's and Soviet Union's territory quickly became the top priority for both nations: bombers carrying nuclear weapons, in fact, were becoming a tangible threat. Meanwhile, the role of radar was acquiring even more saliency. During the 1950s we witnessed the growing threat of radar-controlled missiles, a step forward that immediately put in question the survivability of aircrafts. Through this technology, the radar went beyond its first detection role and became crucial also during engagement, increasing the possibility of killing an approaching enemy aircraft. Surface to Air Missiles (SAMs) guided by radar set off to be the chief preoccupation of strategic air war planners and countermeasures needed to be developed[83]. The War in Vietnam experienced clashes involving American fleets of fighter jets against radar-guided SAM batteries. Pilots rapidly lost their traditional upper hand in battlefields and got forced to perform extreme acrobatic maneuvers in order to dodge missiles, hoping they would

[81] John B. McPeterson (Editor), "The Army Air Forces' 'Confidential' Picture History of World War II", 7th book out of 8, James Patron & Co., 1980

[82] Rebecca Grant, "The Radar Game", Mitchell Institute, 2010

[83] Robert Frank Futrell, "Ideas, Concepts and Doctrine: Basic Thinking in the US Air Force, 1907-1960", Air University Press, 1989

overshoot and so miss the target. However, such dodging maneuvers were not a reliable countermeasure and the risk of SAM engagement affected air operations by narrowing the options for tactical employment, remarkably shrinking them[84]. High speed and altitudes, attainable only through modern technological wonders that were pushing further and further the limits of performance, became the natural responses for new air survivability requirements. The Lockheed SR-71 is a perfect example of an aircraft that can help in properly explaining the strategic environment of its time, despite it not being a combat-oriented vehicle. With its operation ceiling of more than 24 kilometers and a top speed of over Mach 3, the "Blackbird" relied on extreme capabilities such as speed and altitude to grant its survivability during reconnaissance missions, making it too fast and too distant for SAM's missiles: unable to lock their target, the missiles shot usually exploded miles before reaching the vehicle[85]. Merged with electronic countermeasure systems, the SR-71's shape also early probed at the possibility of reducing radar footprint. Nonetheless, the Blackbird was just one-of-a-kind aircraft and had no combat offensive or defensive purposes and was mostly assigned for recognition or espionage[86] like the previous and less successful recon plane from Lockheed-Martin, the notorious U-2[87]. Because of that, in 1974, the USA's Defense Advanced Research Projects Agency and Air Force began a major effort to finally develop combat aircrafts with low radar signature as a top priority, willing to put an end to radar's dominance. American companies Lockheed Martin and Northrop Grumman were pioneers of stealth technology, despite their approaches being completely different at first[88]. Lockheed realized, through its test aircraft Echo 1, that flat surfaces could play a major role in the detection game and so they opted to spread out calculations over

[84] Maj. A. J. C. Lavalle, "The Tale of Two Bridges and the Battle for the Skies Over North Vietnam", USAF Southeast Asia Monograph Series, Washington DC: Office of Air Force History, 1976; Mark Carlson, "Operation Spring High: Thuds vs. SAMs", Historynet, 2019, historynet.com/operation-spring-high-thuds-vs-sams/

[85] Peter W. Merlin, "Design and Development of the Blackbird: Challenges and Lessons Learned", American Institute of Aeronautics and Astronautics, 2009

[86] Jeffrey T. Richelson, "Science, Technology and the CIA", The National Security Archive, The George Washington University Press, 2013

[87] Governmentattic.org, "Beacon Hill Report: Problems of Air Force Intelligence and Reconnaissance, Project Lincoln, Massachusetts Institute of Technology (MIT)", 1952, governmentattic.org/12docs/USAF-BeaconHillReport_1952.pdf

[88] M.W. Browne, "Two rivals designers led the way to stealthy warplanes", The New York Times, 1991

hundreds of facets on the framework of the aircraft. Northrop, instead, relied on the modeling of compound curves while shaping the edges to achieve a more fluid design. These two approaches settled the ground for the development of radar beam-reflecting technology for the future: Northrop's soft curves worked perfectly for deflecting radars beams coming from head, while Lockheed faceting was effective in reducing signature for side and rear incoming radio waves. This last solution was preferred for the development of stealth fighter jets due to maneuverability and avionic requirements, while Northrop's was more fitting for stealth strategic bombers, eventually leading to the creation of the B-2 Spirit Bomber. From then on, once the basic principles of reducing radio beam return were understood, it quickly became all about compromising stealth and performance[89]. Nonetheless, stealth technology is extremely relevant when addressing the collapse of the Soviet Union as well. This technology remarkably forced the Soviet Union to spend all of its resources into defense system that, however, would have been permanently outperformed by stealth technology, including terms of costs: defending the Union's wholesome territory became unachievable and the constant vulnerability to nuclear strikes shake soviets' pillars up to their core, strategically dooming the Soviet Union into a condition of perpetual inferiority[90].

More and more features were successfully implemented into aircrafts with stealth design over the years, allowing them to perform supersonic speed, aerodynamic stability, more operational range and also radar absorbing coating were being tested. Lately, with digital technology overcoming the technological scenario, the implementation of fly-by-wire technology permitted a predominant exploitation of computers to constantly adjust flight controls, paving the way for the modern stealth fighter jets that are known today by the public.

[89] David J. Lynch, "How the Skunk Works Fielded Stealth", Air Force Magazine, 1992, airforcemag.com/article/1192stealth/

[90] Ben R. Rich and Leo Janos, "Skunk Works", Little, Brown and Company, 1994

2.3 How Stealth Works: Technology and Design Principles

Stealth technology is not just one single technology. It is, in fact, a set of technologies, used in combination with each other to greatly reduce the distance at which a vehicle can be detected. Stealth features allow for a reduction of thermal footprint, sound deletion and all those other aspects that would normally be sources of detection. Nonetheless, the most important element of stealth technology as commonly intended, is the capability to reduce Radar Cross Section (RCS) through some specific materials and an *ad-hoc* design[91]. Radar Cross Section, or also called radar signature, is a measure of how detectable an object is by a radar; a measure given by the sum of the major reflective components of the aircraft's shape. RCS is typically measured in square meters and a larger one means that an object can be more easily detected. Reducing a defender's radar range, by shrinking the attacking aircraft's RCS, can imply huge benefits for the attacker. In order to properly understand how stealth works, a presentation on how radars work shall be presented first[92].

RADAR stands for Radio Detection and Ranging. As reported in the book *Understanding Stealth*, "a radar is composed by the following elements: the transmitter, which produces a repetitious series of pulses, a transmitting antenna, that collimates this energy into a fan beam much like a flashlight reflector projects light into a narrow beam, a receiving antenna, pretty much identical to the transmitter antenna but receives energy from defined regions in space, and lastly a receiver/signal processor which must listen for echo receiver relative to the time the transmitter pulse was broadcasted"[93]. Radar's spotting works thanks to electromagnetic waves that, when emitted by the transmitter at the speed of light, clash with an object and, being reflected, bounce back to the receiving antenna like a billiard ball would do, making the location of the target understandable. Then, the radar receiver must try to distinguish an effective intruder from background electronic noise or false target

[91] Rebecca Grant, "The Radar Game", Mitchell Institute, 2010

[92] Maj. Gen. Mark Barrett and Col. Mace Carpenter, "Survivability in the Digital Age: The Imperative For Stealth", Mitchell Institute, 2017

[93] John Shaeffer, "Understanding Stealth", Marietta Scientific, 2018

echoes. Radar's antenna can detect a target only when it is pointed directly at it; so, the receiver must rotate in order to search the skies, always pointing at different special locations. The transmitting and receiving antenna are often the same and if not, they are very close to each other[94]. Of course, distance alone is a relevant variable in considering how much radar echo will a target produce: the further it is, the less electromagnetic waves will be sent back to the receiving antenna. Moreover, the effectiveness of radars' energy waves are limited by the natural curvature of the planet, making them "unreliable over a certain distance of about 500 to 600 kilometers[95]".

For stealth design purposes, reflecting the incoming radar waves is the most important goal to attain. Vehicles with low radar RCS can indeed come nearer to the objective, being detected only when dramatically close to radar sites[96]. Data about the pattern between low RCS and detection distance presented by researcher John Shaeffer is clear: a 1.0 square meters score of RCS allow for a detection up to 100 miles (160 kilometers circa), while an RCS of 0.0001 square meters, like the one supposedly possessed by the F-22 Raptor, can be detected not before the aircraft reaches a distance of 10 miles (16 kilometers) to the site. For comparison, the F-22's RCS is about the same size as a bumble bee[97]. Such performances can be achieved only with extremely complex arrangements and a meticulous projected design. Most importantly, the framework of the aircraft must present specifically shaped surfaces that disperse electromagnetic waves. As described before, these waves behave similarly to a billiard ball: once they hit a surface, they bounce back; the more the surface does not face the radar directly, the more the incoming energy is dissipated. Not returning to the receiver, this dissolution is translated into a better concealment from enemy sensors[98]. So, the purpose of stealth design is to bounce away the incident radar energy from the radar site as much as possible.

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[94] *Ibis*.

[95] Steven Biddle and Ivan Oelrich, "Future Warfare in the Western Pacific", International Security Vol.41, MIT Press, 2016

[96] Ray Alderman, "Radar cross section: The measure of stealth", Military Embedded Systems, 2017, militaryembedded.com/radar-ew/signal-processing/radar-cross-section-the-measure-of-stealth

[97] John Shaeffer, "Understanding Stealth", Marietta Scientific, 2018

[98] Rebecca Grant, "The Radar Game", Mitchell Institute, 2010

This target can be accomplished, first of all, by not having surfaces pointing into those regions that need to appear stealthy, like the front and the wings, which are the primary threat sectors for concealment finality. Flat plates, with a proper angle, can be very effective in achieving radar concealment and the peculiar shape of the B-117 Nighthawk and of the B-2 Spirit Bomber shows perfectly how their frameworks were developed with deep attention towards a low Radar Cross Section. In fact, hard body shaping remains the most predominant solution to lower radar echo and it is what gives to stealth bombers and fighter jets their peculiar look presenting flat and thin surfaces, smooth angles in the front, a very low profile when viewed from the azimuth plane, buried-tail engines and so on[99]. Of course, stealth aircrafts will always present some degree of vulnerabilities from specific angles, due to the fact that "surface and edges must point somewhere in space […] there will always be regions where surfaces and edges have significant echo reflection[100]". In fact, depending on where radar waves "hit" the aircraft, it is possible that its RCS may be higher or lower. For example, engine inlets of planes are a major problem for stealth, because all of the electromagnetic waves that go into the cavity opening come back after reflecting from the walls and engine front face. Latest technologies have overcome this weakness by using electromagnetic absorbing materials coupled with shaping of the duct and engine front face. The duct is shaped to force the incoming energy to bounce from wall to wall, rather than directly expel it. Walls are then coated with absorbing materials in order to absorb as much energy as possible[101]. Twisting and turning inlets is a technique known as framework-buried engines, a solution present on different American-manufactured stealth fighter jets like the F-35 and F-22, whose engines "breath" thanks to a pair of frontal air intakes. Surface roughness is also an important element, given the fact that surface imperfections such as gasps, cracks, rivets and construction joints cause an important scattering that directly lowers Radar

[99] Logan Nyle, "How the legendary B-2's stealth actually works", We Are The Mighty, 2022, wearethemighty.com/mighty-tactical/how-b2-stealth-bomber-works/

[100] Rebecca Grant, "The Radar Game", Mitchell Institute, 2010

[101] John Shaeffer, "Understanding Stealth", Marietta Scientific, 2018

Cross Section. Because of that, stealth technology requires continuous testing and an obsessive attention to every detail[102]. The role of direct and tangible experience is a predominant feature in developing stealth and is what makes it so hard for competitors to imitate such technology. Moreover, some weapons such as laser guided missiles are known to favor radar return and so, every time a stealth aircraft is deployed, even the kind of armament it carries and their quantity can make a considerable difference between being spotted earlier, or not, by enemy radars. Forced to overcome this issue for clear strategic purposes, solutions to hide weaponry inside the aircraft body or other methods of concealment are being employed in 5th generation stealth fighters. Nonetheless, it may seem that fighter jets may look to possess an overall less stealthy framework than stealth bombers. For example, fighter jet's cockpits are well- known scattering sources, because they need to be mobile and all the components that merge the glass with the framework of the plane must be hidden. Their radar echo has been reduced by applying optical transparent metal coatings to the windshield canopy that bounce away the incident electromagnetic energy[103]. All of this was done because in an air engagement scenario, a fighter jet pilot must have a wide window allowing him to have complete visual over its surroundings to properly direct its vehicle and never lose sight of its opponents, something that a bomber's pilot would never need as much: the divergencies in stealth body shaping reflect the different requirements that every aircraft requires, depending of course by its role[104].

In conclusion, is it fundamental to consider that fighter jets need to merge stealth design and techs with supersonic engines and top of the notch avionics, which are required when dogfighting against enemy aircrafts: for them, compromising between stealth and performance has been way more present during development and testing. In fact, being fighters jets, these kinds of vehicles cannot rely only on hard body shaping to achieve supremacy and need to maintain extreme capabilities to assert their

[102] David Baker, "Fifth Generation Fighters", Mortons Media Group, 2021

[103] Maj. Gen. Mark Barrett and Col. Mace Carpenter, "Survivability in the Digital Age: The Imperative For Stealth", Mitchell Institute, 2017

[104] Barrett Tillman and Dan Pedersen, "Top Gun: An American Story", Hachette Books, 2019

dominance in the air when attacking and defending. Some fighter jets may have a higher RCS footprint but their supersonic speed, merged with their supreme maneuverability, still makes them formidable opponents with consistent survivability features[105]. This translates into more adaptability for this kind of aircrafts, a characteristic that no other war plane like a bomber or an air-to-ground air striker could ever possess.

2.4 Stealth and Tactics

When describing the tactical benefits, consequences and effects of the deployment of stealth vehicles in operations, the first element to address is that stealth aircrafts, if coupled with precision guided weapons, can significantly reduce costs when total "mission package" expenses are considered. In order to better explain this point and furtherly prove the reduction of costs that only stealth can imply, I will rely on the example provided by the book *Understanding Stealth*, where it describes a fictional mission that aims to destroy the main communication hub in the center of a heavily defended enemy city. With this instance, the author demonstrates how arming new generation stealth bombers with precise guided weapon can show the absolute overpower that stealth is able to accomplish on the battlefield. Without stealth technology, quoting the paper, "this mission would have required 32 aircraft carrying non-precision bombs, [..] 16 escort aircrafts and 12 vehicles to suppress enemy air defenses. Then, 15 tankers would be required since these vehicles do not possess the required operational range and must be in-flight refueled." So, briefly summarized, this operation would require 75 aircrafts and 132 aircrew. Arming them with precision weapons would shrink the vehicles involved up to a total of 55. Then, if we add stealth capabilities to the aircraft operating, as author Shaeffer explains, we would face a complete cut for air escort and enemy air suppression, since their presence would result to be superfluous. Lastly, if technologically advanced stealth bombers like the B-2 were to be deployed, since they "can carry a much higher payload of precision

[105] Bill Sweetman, "Ultimate Fighter: Lock-Heed Martin F-35 Joint Strike Fighter", Zenith press, 2004

weapons and have much longer range", this mission cost would consist in just 2 aircrafts and 4 aircrew, but the possibilities of success would remain the same[106].

In terms of force deployment, costs and effectiveness, stealth grants overwhelming potentialities for an attacker. Aircrafts with relevant stealth features could be ordered to operate in strict numbers and still be successful while not being more vulnerable, something that would have been unimaginable just 40 years ago. The deployment of F-117s in the 1990 Gulf War furtherly proves this point, remarking how an advanced technology, such as stealth, is not superior intrinsically but, when properly merged with adequate skills and tactics, can be truly determining for conflicts outcome and on-ground losses[107]. During the build-up of the conflict, American planners wanted to deploy large strike packages to pierce Iraqi air defenses; however, when F-117s were made available, strategists completely rethought their plans since these vehicles could operate with minimum, if any, support even when flying in the hearth of combat-ready enemy air defenses. The results attained, lastly, speak even more loudly: "F-117 flew just two percent of the total attack sorties, but struck nearly 40 percent of strategic targets" reports the paper *Imperative for Stealth*[108].

Another possible solution could be choosing to merge stealth vehicles with non-stealth ones in cases of direct attacks against an enemy target. If a State possesses, or has immediate availability, of older generation warplanes and some last generation stealth fighters, it could opt for merging the twos while carrying on a strike mission. Quoting the paper written by experts Maj. Gen. Barrett and Col. Carpenter *The Imperative for Stealth* "stealth is normally most effective when employed in concert with other aircrafts and tactics. […] Adding stealth to a multi-capability force package creates a lethal synergy. Mixing stealthy aircraft with conventional aircraft deception, air defense suppression, and

[106] John Shaeffer, "Understanding Stealth", Marietta Scientific, 2018

[107] Stephen Biddle, "Victory Misunderstood: What the Gulf War Tells Us about the Future of Conflicts", International Security, Vol. 21, MIT Press, 1996,

[108] Maj. Gen. Mark Barrett and Col. Mace Carpenter, "Survivability in the Digital Age: The Imperative For Stealth", Mitchell Institute, 2017

electronic jamming will complicate the enemy's defensive problem by an order of magnitude"[109]. Doing so would furtherly challenge the opponent into the detection game, pressuring it to respond with an immediate engagement against less-stealthy vehicles as priority[110]. This tactic would force the defender to face "visible" threats first, while looking over if other, more concealed, vehicles are operating elsewhere: the current clash may indeed just be a distraction. Only a well-organized defense system with wide resources and formed personnel could stand a chance against such arranged attacks[111]. By grasping the diversion effect, stealth aircrafts would grant an even bigger freedom of movement, likely being spotted only when extremely close to a radar site. This would possibly result in leaving, to the attackers, a sufficient window of opportunity to strike their target before the defender can react and, furthermore, leave the battlefield unharmed thanks to the distraction provided by the others, enhancing survivability chances even furtherly. If the entire fleet was composed by top-of-the-notch stealth features aircrafts, like the USA aims to achieve in the upcoming years, the element of providing disturbance would probably not even be required and, in the future, we could assist to battle scenarios where stealthy aircraft have the ability to ingress and strike with almost no detection by the enemy[112].

For defensive purposes, instead, stealth grants numerous benefits that go beyond survivability. In the case of an airspace invasion, fighter jets would rely on stealth body shaping technology first to elude enemy location sensors while approaching at full speed. By doing so, they would grasp an extremely important surprise advantage which, as we have seen also historically, is a formidable trump card in the air combat domain, where no prospects for natural concealment or protection are provided. In 2013, a peculiar accident between two Iranians F-4 Phantoms and an American F-22 Raptor showed the immense gap in the development of stealth technology between the two States and

[109] *Ibis*.
[110] Rebecca Grant, "The Radar Game", Mitchell Institute, 2010
[111] John Shaeffer, "Understanding Stealth", Marietta Scientific, 2018
[112] Bill Sweetman, "Ultimate Fighter: Lock-Heed Martin F-35 Joint Strike Fighter", Zenith press, 2004

the possible outcome that could have resulted from that encounter[113]. USA-made and operated reconnaissance unmanned vehicles have been shot down multiple times above Iran's airspace over the course of time and, in 2013, it happened that two Iranians F-4s were about to intercept the latest drone operating too close from Iran's border. Being air-to-air combat vehicles, the Phantoms represented a real threat for the drone which stood almost no chances of survival against the two fighters. Aware of their superior fire power and expecting an easy take-down, the F-4s approached rapidly to the aircraft, only to receive a message via radio a few seconds later. Completely concealed by enemy sensors, a Lockheed Martin F-22 Raptor, which was escorting the drone for all the time, was able intercept and then fly under the enemy aircrafts going completely unnoticed. Not being spotted even while inspecting the weapons carried by the above F-4s, only then Lt. Col. Kevin Sutterfield gave up his position by breaking radio silence: rival pilots were warned to retire immediately and, given the absolute predominance position shown by the F-22, they were forced to comply. This close encounter could have resulted in a total superiority of the American fighter if the vehicles ever happened to break into a fight. The F-22's thrust-vectoring acrobatics and advanced avionics would have supplemented the stealthy design even furtherly, to make for what would have likely been a very one-sided fight despite it being outnumbered[114].

If a wider picture of stealth-provided benefits during air combat is considered, it is also possible to address the benefits that stealth technology provides even beyond reducing Radar Cross Section. For example, a technology built upon dissipating heat footprints has good chances of preventing enemy warplane's weapons to lock-on using infrared, one of the most deadly tracing tech, forcing an engagement through gatling guns that, however, imply a lower precision and lethality than any smart

[113] Eli Fuhrman, "An F-22 Stealth Fighter Flew Under an Iranian F-4 Phantom (Undetected)", The National Interest, 2021, nationalinterest.org/blog/buzz/f-22-stealth-fighter-flew-under-iranian-f-4-phantom-undetected-190472

[114] Alex Hollings, "How an F-22 Pilot Scared Iranian Fighters Away With Just One Sentence", SandBoxx, 2021, sandboxx.us/blog/how-an-f-22-pilot-scared-iranian-fighters-away-with-just-one-sentence/

guided weaponry could instead guarantee[115]. When considering electronic warfare, on the other hand, stealth still grants consistent improvement of such capabilities. Equipped with electronic jamming devices, a stealth fighter jet can significantly increase the stealth capabilities of a force package as a whole. The small RCS of a stealth aircraft, if combined with advanced processing and digital control, could make much more easy to use low-power spoofing with on-board Active Electronically Scanned Array (AESA) electronic attack radio frequency system, in order to execute what is known as "digital cloaking", which allows for disappearing from enemy displays[116].

Lastly, of course, it is remarkable to consider that a careful mission planning is still fundamental for the success of every mission and no technology ever will be so overwhelming to completely delete the need to develop a detailed strategy for each one, given the point technology has reached in the military domain up to these days. The process of shooting down an enemy aircraft is still a difficult task to achieve and, in combat scenarios, individuation does not mean immediate kill. Early detection can still provide a quick response to the enemy, allowing it to launch fighters but, once in the air, their ability to detect and engage remains relatively limited against stealthy aircraft[117]. As contested airspace becomes more and more common, stealth still provides significant tangible advantages for attack and defense purposes[118]. Moreover, stealth is proving itself to be not only a viable solution nowadays, but also a fundamental prerequisite for the foreseeable future in air supremacy.

[115] Andrea Gilli and Mauro Gilli, "The Diffusion of Drone Warfare? Industrial, Organizational and Infrastructural Constraints: Military Innovations and the Ecosystem Challenge", Security Studies Vol.25, 2016

[116] Maj. Gen. Mark Barrett and Col. Mace Carpenter, "Survivability in the Digital Age: The Imperative For Stealth", Mitchell Institute, 2017

[117] Rebecca Grant, "The Radar Game", Mitchell Institute, 2010

[118] Robbin Laird, "The Role of Fighters in Contested Airspace: The International Fighter Conference Debates the Issue", Defense.info, 2018, defense.info/air-power-dynamics/2018/11/the-role-of-fighters-in-contested-airspace-the-international-fighter-conference-debates-the-issues/

2.5 Future of Stealth

Stealth is going to become more and more advanced as time goes by. Its unique combination of offensive and survivability capabilities make it a necessary requirement for contemporary and future war air vehicles. It would be wise to suppose that concealment features are going to evolve even further in the upcoming decades but, nonetheless, it is difficult to forecast the features and capabilities of such futuristic machines. With the 6th generation stealth fighter jet racing heating up and supposed to come ahead in the 2030s, it is logical to assume that these last generation aircrafts will push the performance of stealth even beyond, merging it with the cyber dominion and starting to rely on a more and more solid support from artificial intelligence[119]. Possibly, we could witness the start of pursuing methods for signal negation rather than dissipation, so that instead of "bouncing back" radar waves they would actually be removed by some advanced radar absorbing material[120]. A perfect merge with hard body shaping and futuristic matter, maybe enforced by some jamming device, could logically achieve such tasks. With stealth vehicles spreading worldwide, we could also predict a "return" of dogfighting. Since vehicles with stealth features are expected to become more and more common, the surprise effect could become harder to grasp for most of the actors involved in future clashes. Missing the tactical upper hand granted by stealth technology, pilots could only achieve victory through extreme maneuvers and group tactics, since smart precision weapons would be less likely to target-on. Allied, or enemy, ground forces could be likely to face similar challenges and their effectiveness could be consistently limited.

Nonetheless, others experts may suggest that, due to the improvements in stealth and the enhanced development of any kind of precision weapon, dogfighting as traditionally intended is destined to become obsolete. Future air fights could just consist in a desperate research for the enemy vehicle,

[119] EurAsian Times Desk, "Who is Winning the Race between US, Russia & China to Develop World's First Sixth-Gen Fighter Jet?", The EurAsian Times, 2020, eurasiantimes.com/who-is-winning-the-race-between-us-russia-china-to-develop-worlds-first-sixth-gen-fighter-jet/

[120] John A. Tirpak, "The sixth Generation Fighter", Air Force Magazine, 2009, airforcemag.com/article/1009fighter/

relying on different top-of-the-notch scouting technologies such as, for example, the detection of the electromagnetic spectrum. Once the opponent is located, the duel would then peak in a quick take-down due to new generation weapons, providing maximum precision and basically no chances for evasion[121]. This supposed evolution of air combat would, alternatively, make the surprise effect as powerful as it had originally been more than a century ago. Lastly, we could expect to see stealth fighter jets operating with a personal drone escort, which could function for different purposes. Escort drones could be deployed in order to enhance the stealth capabilities of the war plane by providing some kind of radio or cyber disturbance; they could help the pilot in striking its targets, possibly hitting different ones at the same time; or they could act as wing-men, providing defensive support in the case of incoming precision guided weapons or other fighter jets attacking the pilot[122]. Whatever the cases, stealth technology has set new standards for air supremacy and it would be wrong to forecast a future where stealth capabilities are even a inch less fundamental than they are today.

[121] Apoorva Jain, "Dogfighting, Stealth Jets Could Become Osbolete as US, China Looks to Arm Their Fighter Jets with 'New Age Weapons'", The AurAsian Times, 2021, eurasiantimes.com/dogfighting-stealth-jets-could-become-obsolete-as-us-china-look-to-arm-their-fighter-jets-with-new-age-weapons/; Alex Hooling, "Are the days of dogfighting over? An in-depth air combat analysis", Sanboxx, 2022, sandboxx.us/blog/are-the-days-of-dogfights-over-an-in-depth-air-combat-analysis/

[122] John A. Tirpak, "The Sixth Generation Fighter", Air Force Magazine, 2009, airforcemag.com/article/1009fighter/

3. Stealth Countermeasures

3.1 Introduction to countermeasures principles against stealth

Different solutions have been designed over time to shrink down the power of warplanes. If during the 1900s the air force experienced an almost supreme power over the battlefield, as described by the visionary air-warfare theoric Giulio Douhet,[123] the condition changed radically with the invention of radar and, most remarkably, with the coming of radar guided Surface to Air Missiles. Nowadays the United States Air Force, equipped with some of the best stealth technologies available, has gained an important upper hand and big military powers, such as Russia and China, are trying to develop new and improved technologies to stand up to the challenge. Nonetheless, up to these days, the conflicts witnessing the deployment of stealth air vehicles underline how stealth is indeed a deeply challenging technology for air defenders to overcome. As reported by *The Imperative of Stealth*, "air defenses in Iraq (in 1991 and 2001), Serbia (in 1999), Afghanistan (in 2001) and Libya (in 2011) proved largely incapable of dealing with stealth aircraft"[124]. Regardless of the fact that the technologies and tools employed in these aforementioned conflicts were considerably different, stealth still managed to be as deadly as theory suggested in spite of the wide spectrum of "opponents" and different weaponry faced over the years. Indeed, even if an F–117 Nighthawk was shot down in Serbia by a Soviet manufactured surface-to-air missile SNR-125 Neva, probably due to training shortfalls and planning errors, the overall performance and survivability of stealth vehicles has never been put to question[125]. Their remarkable results attained, indeed, are strong pillars for the currently undergoing renewal towards stealth capabilities that the US Air Force is getting through. Theoretically, the key for beating contemporary stealth could be to develop modern solutions to sense an operating aircraft's footprints

[123] Giulio Douhet, "Il Dominio dell'Aria", Historical Office of Italian Military Aeronautic, 2022 (First Edition 1921)

[124] Maj. Gen. Mark Barrett and Col. Mace Carpenter, "Survivability in the Digital Age: The Imperative For Stealth", Mitchell Institute, 2017

[125] Dario Leone, "An In-Depth Analysis of How Serbs Were Able to Shoot Down an F-117 Stealth Fighter During Operation Allied Force", The Aviation Geek Club, 2020, theaviationgeekclub.com/an-in-depth-analysis-of-how-serbs-were-able-to-shoot-down-an-f-117-stealth-fighter-during-operation-allied-force/

like tracing the heat, the sound, the electromagnetic spectrum or even some cyber marks. Considering how modern stealth vehicles were built upon, a hypothetical new sensor technology could grasp away the advantage gained with decades of experimentation with relative ease. However, in reality, radars have not lost even an inch of their traditional backbone position and are still protagonists when operating and coordinating states' defensive systems[126]. That is because the radar still provides the best scouting capabilities, bringing forth an overall positive compromise between resources, cost, maintenance, coordination with weapons systems and surface of the tracked area; a condition that furtherly underlines why stealth has been so appealing to the United States since the beginning. Another relevant element when addressing stealth vulnerabilities consist in Anti-Access and Area-Denial (A2/AD) systems. As explained by Steven Biddle, A2/AD systems are extremely complex and networked structures utilized by states, as the name suggests, to deny any unfriendly incursion and settling above specific geographical areas. These systems, just like traditional clashes between defenders and attackers, follow the "kill chain" procedure consisting of 4 different phases: identification of the target, dispatching of forces against the target, initialization of attack and, lastly, destruction of target. Of course, in order to achieve such a goal, huge capabilities of coordination are requested, as well as technology, to allow for a perfect execution from all the actors involved[127]. Radars will always be the top-threat priority for air attacks and stealth vehicles were designed just to shrink down its effectiveness. Nonetheless, fast information sharing, being what effectively fuels the overall speed at which the whole kill chain can be properly executed, could still be considered as one of the biggest threats for the attackers and, at the same time, one of the most important winning conditions for the defenders to achieve[128]. Stealth vehicles equipped with jamming devices that disturb enemies' communication hubs can raise the degree of challenge by an order of magnitude,

[126] Rebecca Grant, "The Radar Game", Mitchell Institute, 2010

[127] Steven Biddle and Ivan Oelrich, "Future Warfare in the Western Pacific", International Security Vol.41, MIT Press, 2016

[128] Danelle Au, "Snapping Links in the Kill Chain: Lessons Learned by a Stealth Pilot", Security Week, 2017, securityweek.com/snapping-links-kill-chain-lessons-learned-stealth-pilot

eluding conventional tracking tools while, at the same time, harassing enemy's information sharing[129]. Generally, a quick and efficient intelligence distribution among defenders may represent one the biggest threats for an operating stealth vehicle, since it could limit its operative concealment setting on the alarm and, consequently, the whole kill chain procedure, forcing it to operate in a prickly environment or, eventually, to retire.

3.2 Stealth against Radars

As previously stated, radar technology is far from being replaced and the competition between it and stealth aircraft has recently hit the peak. The general technological upgrades had huge repercussions for the execution of the kill chain, which has improved consistently over the last two decades. Being so vital for every defensive system, the radar has become better and better in denying enemy vehicles' concealment and still possesses a fundamental role for the execution of the kill chain, since it is involved from the identification process up to the initialization of the attack[130]. When its tracking capabilities are integrated with Surface-to-Air-Missiles, a typology of ground-to-air weaponry furtherly presented in this chapter, a top-of-the-notch radar can exponentially improve the effective performance of defenders[131]. The recent integration of digital technologies, indeed, has improved sensor range, accuracy and rapidity of the A2/AD apparatus as a whole, making it lethal as never before. Moreover, further implementations to radar technology, in particular for locational accuracy, are expected to pose some challenges to stealth vehicles but it is unclear how much they will prove to be effective operationally speaking. US challengers, for example, have destined a big amount of resources towards the development of "bi-static" and "multistatic" radars systems, implementing them into their A2/AD components. Bi-static radars separate the transmitting antenna

[129] Maj. Gen. Mark Barrett and Col. Mace Carpenter, "Survivability in the Digital Age: The Imperative For Stealth", Mitchell Institute, 2017

[130] John Shaeffer, "Understanding Stealth", Marietta Scientific, 2018

[131] Britannica, "Surface-to-air-missiles", britannica.com/technology/surface-to-air-missile

from the receiver, or from a group of receivers like for the multistatic ones, in order to have more possibilities of collecting back radio waves dissipating from stealth vehicles. This procedure creates numerous synchronization challenges but should provide the ability to process noise and clutter that older radars could not, merged with a "real time" computational signal processing[132]. However, even if they are generally less costly, performance analysis suggests that these bi-static and multistatic radars possess no better detection performance than their predecessors monostatic radars, which are the same ones that modern stealth aircraft have been designed to overcome for decades. Moreover, investments for calibration and advanced signal procedures have been sometimes even higher than traditional radars, making them a less appealing solution to adopt as time goes by[133]. Lastly, it is important to remark how the different antennas for emitting and receiving could actually leave more windows of vulnerability for the attackers, that could deny huge capabilities of radar detection with just few quick and precise strikes[134]. Low-frequency continuous wave radars provide a very interesting alternative to traditional radars and are very tough opponents to hide from, even for modern stealth aircrafts. However, these low frequencies often provide lesser capabilities when pinpointing a target, usually creating a wide "bubble" area where an enemy aircraft may be operating[135]. What is fundamental to underline is that a strategic disposition of radars may play a more predominant role in the detection game than ever before. As it was described previously, there are, and always will be, parts of the aircraft that will be more vulnerable to detection because of engineering compromises and flying requirements. So, for the defenders, the best solution to opt for should be to dislocate their radar systems in strategic locations that are more likely to intercept the return coming from weaker parts of the vehicle's framework. This may indeed help to spot the aircraft

[132] Terje Johnsen and Karl Erik Olsen, "Bi- and Multistatic Radar", RTO NATO, 2006

[133] Rebecca Grant, "The Radar Game", Mitchell Institute, 2010

[134] Maj. Gen. Mark Barrett and Col. Mace Carpenter, "Survivability in the Digital Age: The Imperative For Stealth", Mitchell Institute, 2017

[135] Alex Hollings, "The US' Best Stealth Jets are Pretty Easy to Spot on Radar, but that Doesn't Make It Any Easier to Stop Them", Business Insider, 2022, businessinsider.com/radars-can-see-best-stealth-jets-but-cant-stop-them-2022-7?r=US&IR=T

but tracking it for an extended period of time would still be quite complex even for the more prepared personnel[136]. Nonetheless, if radar waves returns are seized and an enemy activity is suspected to take place, defenders can send fighters to search the area, putting the attackers in danger. Collecting as much intelligence as possible is a key condition both for the defenders and the attackers; since performance, lethality and concealment are being pushed to extremes by latest technology, information, espionage and reconnaissance will become only more and more crucial when determining success or failure in combat. For example, an attacking stealth aircraft which gathered an excellent amount of intelligence, could easily bypass some heavily radar-surveillanced areas and still strike its target, possibly going almost unnoticed by enemy sensors until hopelessly close to it[137]. Stealth technology grants the accomplishment of different solutions and *modus operandi* that would, otherwise, not be achievable with traditional tools[138]. Moreover, the overall strict secrecy about stealth tactics and stealth vehicles' deployment may be a hint reflecting the general force power that only stealth packages are capable of providing.

3.3 Ground-to-Air Countermeasures: SAMs and MANPADs

Advanced Surface-to-Air-Missiles (SAMs) are one of the protagonists that made, over the years, the challenge for air survivability all the greater. SAMs are radar or infrared guided missiles fired from ground position to intercept and destroy enemy aircrafts, or even other missiles. Widely utilized by most countries and currently leaders among anti-aircraft weapons in the modern military, SAMs have, over time, replaced anti-aircraft guns as well due to their battle-proven lethality, pushing them into highly-specialized roles[139]. Modern SAM categories are based on the kind of ammunition they shoot, since missiles capable of traveling far distances are heavier and definitely less mobile, giving

[136] John Shaeffer, "Understanding Stealth", Marietta Scientific, 2018

[137] Maj. Gen. Mark Barrett and Col. Mace Carpenter, "Survivability in the Digital Age: The Imperative For Stealth", Mitchell Institute, 2017

[138] Rebecca Grant, "The Radar Game", Mitchell Institute, 2010

[139] Britannica, "Surface-to-air-missiles", britannica.com/technology/surface-to-air-missile

different SAMs different possibilities of deployment and transport. Such distinction leads to three different categories: heavy long-ranged systems (fixed or semi-mobile), medium-range systems which are vehicle mounted and can fire while moving, and lastly the Man-Portable Air-Defense System, also known as MANPAD, the lightest of them all[140]. All of these models of SAM are equipped with Identification Friend or Foe (IFF) systems in order to avoid friendly fire after identifying a target. These systems are particularly important for long-range detection and engagement batteries; however, even modern MANPADs, that usually rely on human visuals and eye-sight to identify a friendly or enemy target, include this crucial mechanism of distinction[141].

Long-range SAM systems can cover up an area from 150 kilometers, like the Soviet S-300 missile, up to a range of 400 kilometers granted only by the more modern, still Russian manufactured, S-400 Triumf. These kinds of heavy launch systems provide the most extended operational range while offering relatively good mobility and short unlimbering times. Their guidance system, so the means utilized to direct the missile against its target, and early detection are mostly radar-based. Of course, precision of the strikes has been improved exponentially with digital technology and most of modern long-ranged missiles systems' operativeness is limited by radar's natural restrictions[142].

Medium-ranged SAMs batteries have been designed with very different requirements. They feature high mobility and almost no set-up time is required, making them quickly deployable. Moreover, medium-ranged SAMs have been mounted on armored vehicles so that they could be always on the move and ready for a rearrangement, supporting defensive operations but mobile ones as well. Such capacity would turn very effective in conventional war; however, since the 1990s, this

[140] BrahMos Aerospace, "Classification of Missile", brahmos.com/content.php?id=10&sid=9; Britannica, "Surface-to-air-missiles", britannica.com/technology/surface-to-air-missile

[141] Thomas Withington, "Identification Friend or Foe ", European Security & Defense, 2022, euro-sd.com/2022/01/articles/exclusive/24434/identification-friend-or-foe/

[142] Alex Hollings, "The S-400 myth: Why Russia's Air Defense Prowess is Exaggerated", Sandboxx, 2022, sandboxx.us/blog/the-s-400-myth-why-russias-air-defense-prowess-is-exaggerated/

kind of SAM has seen little development due to the rise of unconventional warfare that the international community witnessed[143].

Lastly, it is fundamental to stress the category of MANPADs. These SAM man-portable technologies give huge capabilities to ground forces of taking down enemy helicopters as well as aircraft while ground-attacking. Moreover, MANPADs guarantee maximum mobility since, with their operational weight of about 18 kilos, can be transported and shoulder-fired by single infantry men. First thing first, due to this supreme maneuverability, MANPADs are very difficult to identify during recognition and can always become a sudden danger source while carrying on operations. Their costs are consistently reduced compared to longer-ranged missiles and the air power they provide to ground forces has been remarkable in different warfare contexts and even raised some concerns for terrorist groups possibly utilizing them[144]. With a detection range of about 10 kilometers and an engagement of circa 6 kilometers, MANPADs are no danger for high-flying vehicles like bombers but can be absolutely deadly when an aircraft enters their threat area, such as during air-to-ground attacks. MANPAD missiles rely on different guidance solutions (except radar) to lock-on a target depending on their generation. During the 1960s, the first batteries of MANPADs like the FIM-43 Redeye relied on infrared homing missiles, designed to follow the heat sources of the aircraft, mostly the engines, and then detonate the warhead in proximity of the target. Infrared guided projectiles have proven to be particularly deadly also for the fact that their passive guidance does not trigger any signal when following a heat trace, making them difficult to detect even if the target is equipped with some countermeasures system[145]. As generations progress, infrared guidance has been developed to better focus on the target while deleting any possible background or environmental

[143] Tyler Rogoway, "Ukraine Might Get IRIS-T SLM Surface-to-Air Missile System: Reports", The Drive, The Warzone, 2022, thedrive.com/the-war-zone/ukraine-might-get-german-iris-t-slm-medium-range-sam-system-reports; Air Force Technology, "Medium-Range Surface-to-Air Missile (MRSAM)", www.airforce-technology.com/projects/medium-range-surface-to-air-missile-mrsam/

[144] Marvin B. Schaffer, "Concerns about Terrorists with manportable SAMS", Rand, 1993

[145] Yuferev Sergey, "Fim-43 Red Eye", 2018, topwar.ru/147209-ruchnye-kompleksy-pvo-chast-2-pzrk-fim-43-redeye.html

disturbance. For example, the introduction of Focal-Plane Array (FPA) image sensor technology, which consists of an array of light-sensing pixels, allowed fourth generation MANPADs like the Type-91 to enhance their operational range while boosting precision guidance against the quarry.[146] Another very interesting tool of engagement is laser-guided technology. This beam-riding guidance system possesses a sensor in the tail of the missile, which detects the emission from a laser on the launcher and steers the projectile at the middle of the beam, or even between two beams. Due to this clever solution, laser-guided missiles are able to engage a target from almost any angle and the only condition required is the operator continuously pointing the laser at the enemy until detonation[147]. Because of that, it is very unlikely to jam a laser-guided projectile once it is fired, making this guidance system even more menacing. Extensive training and solid skills are required to properly operate laser guidance but their resistance to traditional countermeasures have made MANPADs like the UK-made Starstreak extremely appealing[148].

Fighter jets possess some countermeasures to face SAMs power. As previously stated, stealth, in military terms, does not mean to be complete invisibility, it means to make your aircraft's detection sporadic while numbing defender's tracking capabilities[149]. Because of that, a possible outcome between stealth against anti-air missiles is an extremely complex topic to address and different operational, decisional and environmental variables may become crucial for the final result. For example, both the F-35 and the F-22 possess liquid-cooled skins and physical structures of their jet-pipes which are designed to reduce thermal signatures, making them generally harder to be locked-on by heat-guided missiles[150]. However a longer operation or a particularly hot environment could

[146] Military Factory, "Type 91 (Hand Arrow)", 2018, militaryfactory.com/smallarms/detail.php?smallarms_id=1181

[147] Army Technology, "The top man-portable air-defense systems (MANPADS)", 2019, army-technology.com/analysis/man-portable-air-defence-systems/

[148] Thales Group, "STARStreak", thalesgroup.com/en/markets/defence-and-security/air-forces/advance-air-defence/starstreak; Army Recognition, "Starstreak Missile Manpad", 2022, armyrecognition.com/british_united_kingdom_missile_systems_vehicles_uk/starstreak_hvm_high_velocity_short-range_surface-to-air_missile_manpads_technical_data_sheet_picture.html

[149] Rebecca Grant, "The Radar Game", Mitchell Institute, 2010

[150] Mark A. Lorell and Hugh P. Laveaux, "The Cutting Edge", Rand, 1998

numb these heat reduction capabilities, allowing ground forces to shoot. In the case of being followed by a laser-guided projectile, an F-35 could positively look for concealment if the environment presents some dense cloud formations, or veer in a way that would make it harder for the operator to follow it through its laser. Then, of course, both fighters could enter and leave the threat area even before any MANPAD is ready to fire. Drones face the threat of SAM relying on their reduced dimensions, linked with a lessened heat footprint due to their smaller engines. Drones' concealment is crucial because it is the characteristic that mostly grants their survivability, since they face almost no chance to elude incoming attacks. Remote piloting, despite being endlessly safer than direct one, makes the whole process of evading incoming attacks way more challenging and current artificial intelligence capabilities may not be developed enough to allow the drone for an autonomous individuation, and then elusion, of different sources of danger. Whatever the case, every kind of stealth vehicle, directly or indirectly piloted, is exponentially more challenging to take down than its traditional counterpart: that is the real deal for its application in the military domain. No technology is so predominant to be, all alone, the key feature for success on the battleground. What is truly important is that some technologies, just like stealth, have the capability to challenge the opponents in a way that makes most of its equipment and strategies less effective, numbing its forces and compromising its threat capabilities[151].

[151] Maj. Gen. Mark Barrett and Col. Mace Carpenter, "Survivability in the Digital Age: The Imperative For Stealth", Mitchell Institute, 2017; Rebecca Grant, "The Radar Game", Mitchell Institute, 2010; Andrea Gilli and Mauro Gilli, "The Diffusion of Drone Warfare? Industrial, Organizational and Infrastructural Constraints: Military Innovations and the Ecosystem Challenge", Security Studies Volume 25, 2016

4. Stealth Fighter Jets

4.1 Introduction to Stealth Fighter Jets: history, technology, and design

Jet fighters are a specific kind of combat aircrafts exclusively dedicated to annihilating enemy air threats in whatever form they may take. Fighters may indeed operate air-to-ground strikes as a means of survival, but their ultimate goal is indeed the achievement of air dominance[152]. Despite the established scenario that currently sees the United States as pioneers and champions of fighter technology, from the early years of World War I until the end of World War II, the USA were actually lagging well behind the leading-edge developments of countries such as the United Kingdom, Japan and Germany. Nonetheless, the experience gained during war times changed the attitude of the US government so that advanced military aircraft research and development started to take place[153]. Researchers Mark A. Lorell and Hugh P. Levaux, in their book *The Cutting Edge*, divide three broad periods of fighter development, where each time window possesses different clusters of technological challenges, military requirements as well as attitude towards the role and importance of fighter jet.

The first period stretches from the 1940s up to the end of the 1950s, where nuclear weapons, merged with the doctrine of massive retaliation, are central protagonists of military and defensive doctrines. In that same time, fighter jets and bombers shifted from piston to turbojet engines, a crucial transiction driven by improvements in aerodynamic's understainding, upgrades in propulsion power and a finer lavoration of materials: these crucial evolutions provided the possibility of achieving supersonic flight. Indeed, 1st and 2nd generation fighters, born during these years, were designed to pursue dominant performances in terms of speed, ceiling and rate of climb, showing innovative entrants matched with some specialized capabilities. The early Cold-War environment, moreover,

[152] David Baker, "Fifth Generation Fighters", Mortons Media Group, 2021

[153] Adam J. Hebert, "Fighters Generations", Air Force Magazine, 2008, airforcemag.com/article/0908issbf/; David Kindy, "The Day Germany's First Jet Fighter Set Soar", Smithsonian Magazine, 2021, smithsonianmag.com/smithsonian-institution/day-germanys-first-jet-fighter-soared-history-180978152/

pushed the American government to fund larger numbers of procurement and technology-demonstration programs[154].

From the beginning of the 1960s until the mid-1970s, we have the second period characterized by an important decrease in new program starts. At the same time, indeed, a new shift toward air vehicle's conception was starting to develop, reflecting the ongoing trends in terms of expenses, deployment and effectiveness. Supported by important personalities such as Secretary McNamara, the idea of multiple and multiservice fighters was being discussed in order to optimize the resources while cutting expenses. In fact, the sudden rise of research and development costs, merged with dramatic changes in procurement approaches by the government and the experience gained in harsh combat scenarios like Vietnam, cast a shadow of uncertainty over fighters' technological requirements and deployment. Multirole appeared as an appealing alternative since traditional development, which focused around speed and altitude, was starting to become financially unsustainable as performances progressed. In the end, both the Air Force and the Navy opted for rejecting the 1950s-like heavier and faster trends, deciding that agile, highly maneuverable features were necessary for fighters to achieve air combat supremacy. Consistent improvements in avionics translated into maneuverability and agility being identified as main performance goals for 3rd and 4th generation fighters, with an important attention destined towards flexibility and multirole granted by new system integration technology[155].

The third and last period goes from the 1970s to the 1990s and is dominated by the stealth revolution. This last period is characterized by exponential advances in technology that enable the achievement of performances and features that could not have been obtained previously, with stealth being definitely one of, if not the, most important of them. As consequnce of these improvements,

[154] Mark A. Lorell and Hugh P. Levaux, "The Cutting Edge: A Half Century of U.S. Fighter Aircraft R&D", Rand Corporation, 1998
[155] *Ibis*.

the competition for leadership ranks in fighter jets and bombers has come closer and closer to the aerospace domain as the limits of air, combat and cyber performances are being pushed closer to the edge. Relying on almost seven decades of evolution, 5th generation fighters outclass previous generations in almost every aspect and their integration with hardware and software technology allow them to operate even in the most advanced warfare environments[156]. Nonetheless, a deeper analysis of 5th generation fighter jets will be presented later on in chapter 4.2.

4.2 5th Generation Stealth Fighter Jets

With the term "5th generation fighter" experts specifically refer to a fighter jet aircraft classification, which features some major technologies developed during the first half of the 21 century. It is commonly believed that the Lockheed-Martin F-22 Raptor, presented in 2005, was actually the first of this new generation batch, being more revolutionary than evolutionary compared to its predecessor[157]. Such kinds of fighters are the most advanced aircrafts currently operational but there is no agreed unanimity regarding the characteristics that a fighter jet must possess in order to be recognized as a 5th generation one. Generally, a fifth generation fighter model shows the following attributes: a stealth framework made from composite materials granting also the possibility to escort weapons and munitions internally; advanced maneuverability integrated with short take-off and landing (STOL) capabilities; engines that allow for prolonged supersonic cruising without afterburners (supercruise); latest and top-of-the-notch avionics; networked data fusion, improving battle data management and so battle awareness; multirole capabilities, mainly of command, control and communication. It is important to remark that not every 5th generation fighter possesses all of the previous features, which makes an overall global classification even harder to achieve. Quoting researcher and writer David Baker "In reality there is no definitive agreement on just what those

[156] Mark A. Lorell and Hugh P. Levaux, "The Cutting Edge: A Half Century of U.S. Fighter Aircraft R&D", Rand Corporation, 1998

[157] David Baker, "Fifth Generation Fighters", Mortons Media Group, 2021

generations represent and where each generation starts or by what criteria it ends. Each source consulted has its own interpretation of what constitutes a specific generation, broadly defined as sequential steps from the first jet fighters introduced to operational service to the present and beyond"[158].

Despite the nomenclature not being universally agreed on, it is of wide consciousness that these aircrafts entail huge capabilities for the actors using them. Indeed, such machines have been designed to improve versatility options, covering roles that go beyond air combat in order to develop further not only their lethality but also their part as communication hubs, reconnaissance tools and some even as cyber-electronic warriors[159]. Fifth generation fighters' cost is also an extremely relevant feature not only for western-related policies and public opinion, but also because it can directly influence alliances and international cooperation. Indeed, the act itself of selling such advanced aircraft to some states may boost partnership among them or erode massive geopolitical stability in areas such as the Middle-East, the Western Pacific and South Asia, favoring the rise of tensions as well as force demonstrations[160].

Latest news suggest that the race for fifth generation fighters is far from being abandoned, with countries such as China and Russia spending more and more resources in order to catch up the technological gap left by the United States. For example, the Chinese fighter Shenyang FC-31 has been the center of different speculations as its stealthy framework, its cockpit, as well as the way its materials were shaped, were shown to be so similar to the F-35 Lighting II that some speculations of

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158 *Ibis*.

159 Lock-Heed Martin, "5th Gen Capabilities", f35.com/f35/about/5th-gen-capabilities.html

160 Shreya Mundhar, "AsF-35 Remains Elusive, Will Indian, UAE Air Forces Be The First Operators of Russia's New Stealth Fighter Jet?", The EurAsian Times, 2021, eurasiantimes.com/f-35-elusive-indian-uae-first-operators-of-russia-new-stealth-fighters/;
David Axe, "Who's Going to Pay for Russia's Checkmate Stealth Fighter? Probably Not Russia", Forbes, 2021, forbes.com/sites/davidaxe/2021/07/22/whos-going-to-pay-for-russias-checkmate-stealth-fighter-probably-not-russia/?sh=fadc03c21ff5

cyber espionage and thievy started to take place[161]. Experts claim that some of the data stolen regarding stealth materials and software technology were later on embodied by the Chinese government into the fifth generation Chengdu J-20[162]. Russia, on the other hand, despite having invested less resources compared to the US and China, still holds a remarkable expertise in manufacturing thrust-vectoring engines and the Sukhoi Su-57, which shows as well sensational stealth and avionic features, proves that the soviet-tradition proficiency in building warplanes has not been lost. With its ultra-modern frame design and *ad-hoc* combat systems, the Su-57 is expected by Russian authorities to outclass western-fighters in the upcoming years. Until now, the only weakness possessed by this aircraft seems to be the extremely long construction-time it requires: by the end of 2017, only 9 Su-57 prototypes were reported to be airworthy, showing that the Russian supply chain, as well as their industrial system, still has major maneuvers for improvement[163]. Moreover, Moscow currently is facing the recent economic restrictions introduced by the European Union, which are expected to have somewhat of an impact on Russia's military supply chain, and in particular on furnishing highly-technological gears that only 5th generation fighters require. Nonetheless, it is difficult to precisely forecast the impact of economic sanctions against such a complex industrial system. Only time will tell if the ongoing economic competition will negatively affect Russia's military aeronautic supply-chain in some ways or if Moscow will be able to develop its advanced fighters with the same intensity as before.

Currently, even less powerful countries are developing their own fifth generation fighters, possibly aiming at acquiring more independence from the USA's weaponry while remarking their presence in highly contested geographical areas. South Korea, fueled by the constant threat posed by its Northern

[161] Kelsey Atherton, "CMMC: Stopping Cyber Espionage Like Chinese Theft of F-35 Data", BreakingDefense.com, 2021, breakingdefense.com/2021/02/cmmc-stopping-cyber-espionage-like-chinese-theft-of-f-35-data/

[162] David Baker, "Fifth Generation Fighters", Mortons Media Group, 2021

[163] David Baker, "Fifth Generation Fighters", Mortons Media Group, 2021; Valius Venckunas, "Fact check: How many Sukhoi Su-57 Fighter Jets does Russia have?", Aerotime Hub, 2022, aerotime.aero/articles/31982-fact-check-how-many-su-57s-does-russia-have

counterpart, is carrying on a developing program for its KF-X fighter jet with 20% of the fund coming from Lockheed-Martin itself[164]. In order to face the rising power of China, Japan has repeatedly carried on deep cooperation with the US military in developing some of the latest weaponry technologies, so it is no surprise that the Mitsubishi X-2 Shinshin fighter jet prototype still holds quite relevance in addressing the future of the Japanese indigenous aerospace industry[165]. Turkey as well has placed extremely ambitious targets when developing its new multirole fighter with the TAI-TFX program. Breaking its decades-long tradition of attaining military stocks through western countries and NATO, Turkey aims to construct its own fighter strong of its own latest innovations in military technology, including unmanned vehicles, despite having to borrow engines from European or Russian sources at first[166]. Now in partnership with the Swedish SAAB and British BAE Systems, TFX C100 and TFX C200 service introduction is scheduled for 2029 where a completely new engine, born thanks to a collaboration between Turkey's Kale Group and Rolls-Royce, will be presented[167].

With more and more uncertainty regarding the leading role of the United States in the global political balance and a possible switch towards a multi-polar international asset in the upcoming decades, it is no surprise that so many countries have joined the competition for 5th generation stealth fighter jets, pointing to empower not only their air forces but also their industrial apparatus, know-how, and overall absorptive capabilities.

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[164] David Baker, "Fifth Generation Fighters", Mortons Media Group, 2021; Brian Kim, "South Korea unveils prototype of homegrown KF-X fighter jet", Defense News, 2021, defensenews.com/industry/techwatch/2021/04/09/south-korea-unveils-prototype-of-homegrown-kf-x-fighter-jet/

[165] David Baker, "Fifth Generation Fighters", Mortons Media Group, 2021; Air Force Technology, "Mitsubishi X-2 Shinshin (ATD-X) Advanced Technology Demonstrator", 2016, airforce-technology.com/projects/mitsubishi-x-2-shinshin-atd-x-advanced-technology-demonstrator/

[166] Burak Ege Bekdil, "Turkey officially launches competition for TF-X fighter engine ", Defense News, 2022, defensenews.com/miltech/2022/07/11/turkey-officially-launches-competition-for-tf-x-fighter-engine/

[167] David Baker, "Fifth Generation Fighters", Mortons Media Group, 2021

4.3 Differences Between 5th Gen. Fighter Jets and Previous Models

As previously quoted, there is no clear line that divides last generation models with their previous counterparts. Nonetheless, it is possible to address how different political influences, economic conditions and war-environments can have deep influences on the finality and performance required for fighter jets. In particular, being part of the second age, it could be expected that 4th generation stealth fighter jets do not differ that much from their newest models, possibly bringing small improvements in already efficient features or characteristics. Reality, however, shows that the gap left by 5th generation ones possesses more of a revolutionary footprint rather than just evolutionary, a step forward made possible only by exploiting the latest digital, aeronautic, sensoring and material technologies. However, when addressing the topic of 4th gen. fighters, it is fundamental to consider that this generation was overall perceived as successful since most of this kind of aircraft, like the Mikoyan MiG-29, General Dynamics F-16 and Dassault Rafale are still in service and operative.

4th generation fighters were the first to bring forth some crucial innovation elements that later on will be integrated, and improved, in future models. The general switch from analog technology, in particular for avionics, to digital one is definitely one of the most remarkable achievements. With the F-16 we witness the integration of the so-called fly-by-wire technology, an advanced control system for the aircraft that replaces conventional manual controls with an electronic interface. Fly-by-wire allows for an extremely precise guide of the aircraft: when manual control movements are executed, they are immediately converted into electronic signals transmitted by wires; then the fly computer processes the signals and determines how to move the actuators at each control source depending on the input it received. This formidable evolution translates in a superior agility of the vehicle and in general a better overall maneuverability, features for which 4th generation fighters have become celebrated for. Nowadays, 5th generation fighters have pushed this technology even further and, in combination with more modern and lighter engines, are capable of achieving new standards of arial control and dexterity. The most intensive improvements have been carried on at software level,

enabling a more connected and smoother responses of the sensors from the input of the pilot that are later on translated into a superior maneuverability[168].

The F-16 was also pioneer of another important evolution, being one of the firsts to implement a bubble-shaped canopy that allowed the pilot to experience an almost 360 degree vision without compromising too heavily on its stealth features. Moreover, the whole cockpit and head-up display were built with an important emphasis toward ergonomy, aiming to improve the human interface between crew and systems. For example, the F-16 features an interesting technique known as Hands On Throttle And Stick (HOTAS) which puts all the critical controls, like the weapon release, into side-mounted control stick and throttle in a way that consent the pilot to properly reach any command even while performing high intensity g-maneuvers or dogfighting[169].

Among all the other 5th generation fighters, the F-35 is the one that brought ergonomy, battle awareness and complessive visuals to a new state of art: because of that, the gap left behind with previous generations fighters is remarked in a way that has never been so consistent before. Moreover, most differences are focused around elements that go beyond simple performances about speed and range. The latest technologies implemented in 5th generation fighters, indeed, had such a deep impact on the fighter's capabilities that the gap between 5th and 4th generation is noted by some experts to be more revolutionary rather than evolutionary, with the newest fighters being conceived not only as deadly machines but as complete as well as mobile data gatherers too[170]. For Example, every F-35 pilot possesses an *ad-hoc* made helmet, fully customized over the pilot's head and facial features. Such attention to detail is required because, among all the other capabilities provided by such helmet, the integration following the pilot gaze is so well developed that basically allow for an x-ray vision:

[168] Frederic P. Miller, Agnes F. Vandome and John McBrewster, "Fourth generation Jet Fighter", Alphascript Publishing, 2011

[169] Peter Aleshire, "The Eye Of The Viper: The Making of an F-16 Pilot", Lyons Pr, 2005

[170] Jeffrey W. Hamstra, "The F-35 Lighting II: from Concept to Cockpit", Amer Institute of Aeronautics, 2019; David Baker, "Fifth Generation Fighters", Mortons Media Group, 2021;

when the pilot looks at his feets in the cockpit, thanks to the camera system mounted all around the aircraft, he is actually able to see straight through the framework[171]. Helemt's capabilities, moreover, are even furtherly implemented with attributes such as night vision, infrared vision, information about the aircraft's condition, targeting data, live position of enemy or allied vehicles, and more[172]. The integration of such an advanced piece of technology would not be possible on previous generation models, since the quantity of data and inputs to manage are so complex that only the most recent software are able to process them correctly, a characteristic that helps to understand the revolutionary array that only 21st century technology was able to reach, and then implement, in the newest aircrafts. Perpetual data elaboration and management, indeed, currently hold extremely relevant roles for contemporary as well as future warfare, in a way that was not even imaginable during the 1970s[173].

Indeed, the overall gap existing between fifth generation and fourth generation fighters consists in a wide gap and would technically leave room for extended analysis on every single detail involved in such technological revolution. Generally, however, it is widely acknowledged that 5th generation fighters did not even start their development from their older counterparts, as it used for previous models. Reality is that fifth generation fighters are developed of course for contemporary battle scenarios, but also for those that will exist in the future: this is why the room for comparison between older and latest generation is shrinking consistently as research and development goes by. Aircrafts such as the F-35 entail the possibility to combat and operate in areas that would make every other previous generation fighter an easy target for the enemy. Moreover, the exponential advancements in military technology that took place in the last 25 years are so revolutionary that leave really little

[171] Roger Mola, "Super Helmet", Smithsonian Magazine, 2017, smithsonianmag.com/air-space-magazine/super-helmet-180964342/

[172] David Baker, "Fifth Generation Fighters", Mortons Media Group, 2021; David Roza, "An F-35 helmet costs more than a ferrari and takes two days to get fitted", Task & Purpose, 2021, taskandpurpose.com/tech-tactics/air-force-f-35-helmet-fitting/

[173] Lock-Heed Martin, "5th Gen Capabilities", f35.com/f35/about/5th-gen-capabilities.html

room for what to expect next in the forecastable future in terms of stealth capabilities, speed, avionics, and software technology.

4.4 5th Gen. Stealth fighter Jets' champions: the F-35 and the F-22

Among all models of 5th generation stealth fighter jets, the prodigies presented by Lock-Heed Martin are definitely among the most advanced, currently operational, ones. The F-22 Raptor is considered to be the proper first 5th generation fighter[174] and a lot of its features, as well as stealth capabilities, have been adopted into its cheaper, less secreted, but not less impressive counterpart, the Joint Strike Fighter F-35[175]. Embodying the pinnacle of western-manufactured war planes, such aircrafts are still paving the way for future development of fighters, with their performances setting the standards that the competitors are forced to surpass. Nonetheless, these two models own very different characteristics on both the engineering side as well as the operative. Costs and availability also are extremely different.

The F-22 Raptor was born through a twenty years long development program which started in 1981. Back then, the United States Air Force was willing to expand its air fleet with a new advanced tactical fighter that could possibly supersede the notorious F-16 in the upcoming years, embodying sophisticated stealth features supported by powerful engines. The United States wanted indeed to face the Soviet-manufactured Su-27 Flanker, believed to be the main opponent in the race for air-to-air combat superiority. Considered one of the best aircrafts of its time for dogfighting, the Su-27 possessed superior maneuverability, powerful twin engines and a big load of weaponry[176]. With Washington having witnessed the potential brought by F-117's low-observable capabilities, stealth

[174] Ashish Dangwal, "World's 1st Fifth-Gen Fighter Completes 25 Years! Lockheed, Boeing, USAF Celebrate F-22 Raptor's Global Dominance", The EurAsian Times, 2022, eurasiantimes.com/worlds-1st-fifth-gen-fighter-completes-25-years-lockheed-boeing/

[175] Bill Sweetman, "Ultimate Fighter: Lockheed Martin F-35 Joint Strike Fighter", Zenith Press, 2004

[176] William Cobb, "The Sukhoi Su-27 Flanker, the Masterpiece of Soviet Design that found itself on Opposite Sides of the Russia-Ukraine War", The Aviation Geek Club, 2022, theaviationgeekclub.com/the-sukhoi-su-27-flanker-the-masterpiece-of-soviet-design-that-found-itself-on-opposite-sides-of-the-russian-ukraine-war/

quickly became the top priority for the new fighter in development, with the goal of making it capable of taking down not only currently existing fighters but future ones as well. Big companies such as Boeing, General Dynamics, Northrop Grumman and Lock-Heed Martin participated in a governmental bid against each other in order to grasp the opportunity to develop the most advanced tactical fighter ever. In the end, two prototypes stood out: the YF-22 from Lock-Heed and the YF 23 from Northrop. Both vehicles featured advanced components and high lethality; nonetheless, the YF-22 was preferred by the Air Force since it had the most room for future developments and was technologically less prone to trade-offs[177]. The aircraft's shape itself was one of the most challenging aspects for Lock-Heed Martin and was subject to numerous re-designs over time, since it had to accommodate a wide spectrum of maneuverability and aerodynamic prerequisites, incorporating two thrust-vectoring supercruising engines while, at the same time, maximizing the stealthy hard body shaping[178]. With 750 aircrafts commissioned by the original contract, the Soviet Union collapsed just when the F-22 was about to begin pre-production. This event had heavy consequences on the whole fighter program: the aircrafts planned for construction were cut down to 648 units in 1996, then to 277 in 2004 and lastly to 183 in 2006. Of course, these cuts reflected the security-military environment of the time: with the main challenger of the US disappearing, the quest for an advanced tactical fighter quickly fell down from national priorities. Despite the huge costs for both production and maintenance, different allied countries such as Australia and Japan expressed their interest in buying the F-22 and Lock-Heed hoped to open its masterpiece to public sales as soon as possible, in order to economically face the sudden cut-down ordered by the government. The Congress, however, with an ad-hoc federal law[179], prohibited the exportation of F-22 models to any foreign country,

[177] Mike Wallance and Bill Holder, "LockHeed-Martin F-22 Raptor", Schiffer Military, 1998

[178] David Baker, "Fifth Generation Fighters", Mortons Media Group, 2021

[179] Congress.Gov, House Amendment 295-105th Congress (1997-1998), Page 100, after line 15, SEC.8103, congress.gov/amendment/105th-congress/house-amendment/295?r=5&s=7

mainly in order to keep international top-secrecy on the fighter's stealth and software technologies hidden over as well as under the framework[180].

The choice adopted by the US government is understandable at last. The F-22 Raptor is unique for being the first aircraft to incorporate specific features that set the standards for future 5th generation fighters, with some of them still struggling to implement features that the Raptor had since the first years of service. Some of such capabilities reside, for example, in the twin engines which not only allow the F-22 to supercruise, provide thrust-vectoring power and reach speed of over Mach 2, but were also designed to be smoothly merged within the whole framework, not compromising on any stealth feature. Moreover, the F-22's engines allow for an impressive maximum operating range of more than 3'000 kilometers, improving its general combat operativity. The stealthy framework, composed of radar-reflecting materials, provides an estimated Radar Cross Section of just 0,0001 square meters under ideal angles and altitude, with F-22's official RCS being a highly classified information[181]. Researcher and expert David Baker makes an interesting observation when addressing the stealth capabilities possessed by the F-22 for contemporary standards, quoting how "an inconsequential benefit from the ghostly, flickering register (by the enemy, ndr.) of a stealthy aircraft in the vicinity may work to the advantage of the Raptor, securing the attention of adversaries without presenting a sufficiently strong signals for a lock-on"[182].

Nonetheless, the F-22 also shows remarkable upgrades in terms of sensor fusion and intralinks in a single platform. These evolutions grant to the F-22 the capability to cover fundamental strategic roles when operating in the skies. For example, in a hypothetical battle scenario, the Raptor can exploit its stealthiness in order to get close to the battlefield and operate as a "swarm" leader, designating targets between adjacent aircrafts to take real-time mission management out of the

[180] David C. Aronstein, Michael J. Hirschberg and Albert C. Piccirillo, "Advanced Tactical Fighter Origins of the 21st Century Air Dominance Fighter", AIAA Education, 1998
[181] Bill Sweetman, "F-22 Raptor", Zenith Press, 1998
[182] David Baker, "Fifth Generation Fighters", Mortons Media Group, 2021

traditional AWACS (Airborne Early Warning and Control) aircrafts area, getting ahead of them and closing down on the enemy before the battle management team can transmit instructions to other planes operating in the combat zone[183].

Despite the magnificent wonders performed as well as possessed by the F-22, and its revolutionary role in the evolution of fighter jets, it would be wise to underline how this aircraft still possesses some vulnerabilities. Among them, the most important one seems to be its extremely specific battle deployment. In fact, the F-22 was designed to be an air superiority vehicle, projected to excel in air-to-air combat and, despite having achieved such goals, it is still not enough for it to be considered the backbone of a nation's air force. Examining the high costs of 120 millions USD dollars to purchase and an estimated 68'000 dollars per hour to operate[184], the F-22 will always represent a prodigy of modern technology but lacks a fundamental characteristic that inherently affected its life in service from the beginning. In particular, a general lack of versatility is indeed considered what the Raptor is desperately missing the most. The elevated costs needed to sustain its operational condition are not likely to completely pay-up with such a specific, air-to air dominance role and really few countries may have the resources to keep a fleet of Raptors operational, even if they were able to purchase them with some extremely improbable concessions. Lock-Heed Martin took accurate notes of these related complications and a lot of the F-35 features reflect how the engineers tried their best to overcome the operational and costs limits faced by the F-22, with the willingness to create a fifth generation stealth multirole fighter with an "affordable" price that most nations would be absolutely interested to operate.

Indeed, the F-22 and the F-35 are deeply connected. The F-35 is a 5th generation stealth fighter jet that was born following the progress of the Joint Strike Fighter program, created by the United States

183 *Ibis*.

184 Colin Ritsick, "How much does an F-22 Raptor costs", MilitaryMachine.com, 2021, militarymachine.com/f-22-cost/

and most of its allies with the aim to replace different role aircrafts (fighters, strikers and ground attackers) with a single multi-role platform. The competition witnessed the victory of the prototype presented by Lock-Heed Martin, the X-35, over its Boeing's counterpart, the X-32, after a rivalry that lasted 8 years starting in 1993 and concluding in October 2001. The whole development of the F-35 is probably one of the most challenging engineering dares of recent history, with an enormous spectrum of capabilities and features that the fighter had to incorporate in order to be an almost "omni-role" aircraft, as the Chief of Staff of the Italian Air Force Alberto Rosso describes it[185]. Because of the inherently possessed versatility, different experts claim that the F-35 can be considered the most advanced tactical fighter currently in existence. The vehicle's performances seem to justify such a claim. The F-35 possesses advanced stealth features, is capable of performing strike as well as air superiority missions while being able to provide reconnaissance, intelligence, surveillance and even electronic warfare capabilities: no other fighter in the world embodies such versatility options in just one single platform.

When we consider the whole political, industrial and economic aspect, the F-35 capabilities become even more astonishing. Learning from the "mistakes" made with the Raptor, Lock-Heed's engineers knew from the beginning how their new piece of art had to respect one extremely important provision: the costs, both for purchasing the plane and for maintaining it operative, had to be drastically inferior to the F-22's. This is particularly hard to achieve for stealth vehicles, since their top-of-the-notch technology is vulnerable to environmental deterioration. Because of that, new generation stealth aircraft require continuous maintenance with way more intensity than previous models; moreover, their replacement parts are traditionally expensive and complicated to build in. Despite the challenging nature of the Joint Strike Fighter program, Lock-Heed was able to develop the F-35 Lighting II as a solid stealth multirole platform possessing a single turbofan engine,

[185] Fabio Tognolo, "Initial Operational Capability per gli F-35 Lighting II Italiani", Aviaspotter.it, aviaspotter.it/initial-operational-capability-per-gli-f-35-lightning-ii-italiani/?lang=en

advanced stealth capabilities, live battle data management, two internal weapons bay, an operative range of circa 2'200 kilometers (combat range is about half of that value) and a special BAE Systems' technology, which enable it to perform electronic attacks and to reveal when some electromagnetic threats are incoming against[186]. As the development proceeded, the F-35 was then declined in 3 different versions in order to satisfy U.S. Air Force's, Marine Corps' and Navy's operational requirements[187].

The basic version of the F-35, the F-35A, is the one destined to the United States Air Force and to export in countries that participated in the program: Australia, Israel, Italy, Japan, Netherlands, Norway and the United Kingdom[188]. The F-35A features conventional landing and take-off capabilities and so it requires traditional runways, but is indeed the smallest and most agile of the three versions. It features an overall lighter weight and has the capability to take on g-force up to 9g, features that make the F-35A the version crafted for air dominance mostly, showing more agility, speed and so maneuverability while compromising on some deployment possibilities, since its reliance on air force style runways to take-off[189]. The F-35B is probably the most "spectacular" version of the F-35, since it can perform vertical landing and short take-off (STOVL). This is made possible by a second hidden fan mounted behind the canopy into the framework that opens up stabilizing the air flow. At the same time, the main single engine twists and turns its exhaust flow directly to the ground in order to provide the needed power to lift the aircraft up in the air. Stability during the maneuver is produced by various doors and nozzles that open up and settle coordinated by the plane software systems. Of course, in order to achieve such an advanced maneuverability, the F-35B was the one that had to compromise the most in terms of weaponry and tank capacity, which were reduced to allow the built-in of the complex STOVL system. Nonetheless, its short takeoff and

[186] Bill Sweetman, "Ultimate Fighter: Lockheed Martin F-35 Joint Strike Fighter", Zenith Press, 2004;
[187] Jeffrey W. Hamstra, "The F-35 Lighting II: from Concept to Cockpit", Amer Institute of Aeronautics, 2019
[188] Lock-Heed Martin, "F-35 Brochure", lockheedmartin.com/content/dam/lockheed-martin/aero/f35/documents/F35_Brochure_5_2022.pdf
[189] David Baker, "Fifth Generation Fighters", Mortons Media Group, 2021

vertical landing provide a huge window of different solutions in terms of operativity, allowing it to take off even in the harshest conditions that are likely to be found in the first lines[190].

Lastly, the F-35C is the newest variant of the three and accommodates most of the needs that aircraft carriers require. This version was designed to excel in the Navy's environment, featuring Catapult Assisted Take-Off But Arrested Recovery (CATOBAR) capabilities that were developed to better accommodate the aircraft with carriers' arrest wires and a reinforced tail hook, which are used to furtherly slow down the plane when it lands on deck. The F-35C possesses wider and longer wings to support its low-speed maneuvers and carrier catapult shots; moreover, the wings' extended dimension grants to the C-variant the biggest tank capacity out of the three, a feature that comes in handy considering the severe environmental conditions where only carriers are found to operate. Furtherly, in order to be as efficient as possible, such wings can retract in order to store more vehicle units on board[191]. In the early stages of development, which are currently undergoing for the F-35C, its radar absorbing materials faced hard times due to the constant exposure to eroding agents, such as marine saltiness, forming supposed rust over the framework. Apparently, however,the US Navy claimed that the "rust" photographed on its F-35Cs was not actual rust, since the F-35's frameworks are not built from iron. Nonetheless, both Lock-Heed and the Navy have still quite some experience to acquire about how to perform top maintenance even without specialized facilities, and the sea operational environment should present enough challenges and opportunities to potentially overcome such problems in the long run[192]. Of course, generally, the more a vehicle is advanced and complex, the more its vulnerabilities to external agents rise[193].

[190] Jeffrey W. Hamstra, "The F-35 Lighting II: from Concept to Cockpit", Amer Institute of Aeronautics, 2019

[191] David Baker, "Fifth Generation Fighters", Mortons Media Group, 2021

[192] Thomas Newdick and Tyler Rogoway, "The F-35C 's radar-absorbent skin is looking pretty rough after months at sea", TheDrive.com, thedrive.com/the-war-zone/44067/the-f-35cs-radar-absorbent-skin-is-looking-pretty-rough-after-months-at-sea

[193] Andrea Gilli and Mauro Gilli, "Why China has not Caught Up Yet", International Security Vol.43, MIT Press, 2018

Overall, it is important to remark that the F-35's development has been subject to different criticism by the public, in particular during the early stages. Many in fact believed it impossible to effectively merge such a wide spectrum of capabilities in just one single aircraft. Comprises were suspected to be too overwhelming, in a way that would have made the vehicle not excel in any particular field, questioning its effective operational capability since the unforgiveness of military air domain. Moreover, its weight and important dimensions were considered as weaknesses in a hypothetical dogfight against Russia's fighters[194]. In the end, however, Lock-Heed Martin was able to properly face all the troubles that arose as the project progressed, *de facto* creating an aircraft like nobody else has ever done before[195].

With an average cost of 80 million USD dollars per unit (the A, B and C versions have slightly different price tags), no other fifth generation fighter provides the same capabilities as well as versatility like the F-35 Lighting II does, leaving moreover a wide space of maneuver for future, more complex, implementations[196]. The F-35 was designed to be the effective backbone of USA and NATO air fleets, with the American Air Force ordering more than 1'000 units in different versions[197]. Until now, the F-35 has shown all the chances to be up to such a task. Its versatility, as well as wide deployment from different countries, face no competition by other foreign powers whatsoever: the new Su-57 Checkmate is a clear attempt by Moscow to replicate the versatility and public appeal that only the F-35 has been able to achieve up to these days, even if only Argentina, Vietnam and India have shown some interest for obtaining the developing aircraft[198]. Meanwhile, the numerous purchases of F-35s by Western allies in the last decade have reinforced their strategic relations with

[194] David Baker, "Fifth Generation Fighters", Mortons Media Group, 2021

[195] Alex Hollings, "How the F-35 flies the line between failure and success", Sanboxx, 2021, sandboxx.us/blog/how-the-f-35-flies-the-line-between-failure-and-success/

[196] Valerie Insinna, "F-35 to get more expensive in next deal, program exec says"; Breaking Defense, 2022, /breakingdefense.com/2022/03/f-35-to-get-more-expensive-in-next-deal-program-exec-says/

[197] Lock-Heed Martin, f35.com/f35/global-enterprise/united-states.html

[198] Dmitry Sudakov, "The Checkmate: Unique peculiarities of Russia's new fighter aircraft", Pravda.ru, english.pravda.ru/news/science/71220-checkmate/

the United States, actually shaping the distribution of forces around the world in favor of the USA long-questioned hegemony, elevating the overall air force package of the West by an order of magnitude for contemporary and future combat standards.

5. Drones

5.1 Introduction to Drones

Belonging to a fighting-specific category of Unmanned Aerial Vehicles (UAVs), Unmanned Combat Aerial Vehicles (UCAVs), also known as "combat drones" or simply "drones" referring to the battle domain, are autonomously or remotely piloted aircrafts that perform different military and non-military tasks. They are generally used for intelligence, surveillance, target acquisition as well as reconnaissance missions by different armed forces all around the world[199]. Drones' deployment and availability is supposed to grow consistently in the upcoming years, with over 50 different nations manufacturing various types of unmanned aerial vehicles and more than 4'000 development programs being currently carried on around the globe[200]. Drones inherently possess features that have raised nations' interest over the years. Some of them include supposed low costs of production, high versatility and expendability, merged with high lethality and advanced target acquisition[201]. The effect of modern drone technology in contemporary conflicts is still unclear and researchers have shown different opinions about the topic. Nonetheless, drone-like tools have been used in conflict dating back up to 1849, when Austria attacked the city of Venice with explosives-stuffed air balloons. Despite the attack being recorded as unsuccessful, mostly due to weather conditions, the principles that drove the execution of such strike were very similar to today's ones about drones employment[202]. Today, the principal controversies surrounding the topic are linked to clear ethical complications that

[199] Reg Austin, "Unmanned Aircraft Systems: UAVS Design, Development and Deployment", Wiley, 2010

[200] Government Accounting Office, "Agencies Could Improve Information Sharing and End-Use Monitoring on Unmanned Aerial Vehicles Exports" (Washington DC: GAO, 2012); Dan Parsons, "Worldwide, Drones are in High Demand", National Defense Magazine, 2013, nationaldefensemagazine.org/articles/2013/5/1/2013may-worldwide-drones-are-in-high-demand

[201] Christopher Coker, "Warrior Geeks: How 21st Century Technology is Changing the Way we Fight and Think About War", Hurst Publisher, 2013

[202] Kashyap Vyas, "A Brief History of Drones: The Remote Controlled Unmanned Aerial Vehicles (UAVs)", Interesting Engineering, 2020, interestingengineering.com/innovation/a-brief-history-of-drones-the-remote-controlled-unmanned-aerial-vehicles-uavs

arose when arming semi-autonomous machines with deadly weapons[203]. In particular, International Relations researchers warn that we may indeed be starting a "drone revolution" in the military domain[204], an extremely complex as well as intriguing topic that will be later on presented and explained in chapter 5.3. For now, the goal of this chapter will be to present a series of information required to properly understand drones in security studies. So, a clear picture of their history shall be presented first, as well as their recent growing involvement in military affairs. Then, I will address the possible consequences of such behavior and, lastly, if drones have what it takes to undermine 5th generation stealth fighter jets' supremacy in the skies. The book *The Future of Drone Use* by researcher Bart Custers presents some historical records of the evolution of drone's technology throughout the 20th century, which sometimes has overlapped with inventions that led to Loitering Attack Munitions' (LAMs) creation like cruise-missiles. Nonetheless, drones and LAMs missiles have a significant difference: where the cruise-missiles-like explode when hitting the target, without the capability to gather real time information, most drones models are actually designed to launch their weaponry and then come back to the base safely, all while providing reconnaissance and intelligence. Nonetheless, the line which separates some models from advanced LAMs can sometimes be very thin, with several drones being more similar to warplanes and others being more like smart missiles[205].

During World War I, the first approach to drone technology was achieved by the American manufactured Hewitt-Sperry Automatic Airplane in 1971, developed for military purposes. In 1918, the Kettering Bug was successfully launched and was able to strike targets up to a distance of 120 kilometers while cruising at a speed of 80 km/h circa. The War however ended before both prototypes could witness the battlefield. During World War II, the USA experienced the first massive drones'

[203] Peter L. Bergen and Daniel Rothenberg, "Drone Wars: Transforming Conflict, Law and Policy", Cambridge University Press, 2014

[204] P.W. Singer, "Wired of War: The Robotics Revolution and Conflict in the 21st Century", Penguin Press, 2009

[205] Brennan Devereaux, "Loitering Munitions in Ukraine and Beyond", War On The Rocks, 2022, warontherocks.com/2022/04/loitering-munitions-in-ukraine-and-beyond/

production, with around 1'500 OQ-2 units manufactured by the hands of the Radioplane Company. The OQ-2, considered the first of UAVs, was used as a target-drone during training of anti-aircraft crews. Based on the design of a conventional aircraft of the time, the OQ-2 did not present any cockpit or room for the pilot. Instead, it was launched through a catapult and then recovered by parachute. With the Cold War taking over the world, drones saw wider usage: the MQM-57 Falconer was the first drone deployed for aerial reconnaissance and it first flew in 1955. During the Vietnam War, the US marked the first time in history of large scale drone deployment for reconnaissance goals. At the same time, drones also began to be used in a wider range of new roles such as acting as decoy in combat or launching missiles against fixed targets[206]. Of course, it is important to remark that all the previously quoted historical events of drone deployment were heavily limited by the technology of the time; indeed, only the most recent advancement in hardware and software technologies, as well as GPS integration systems, allowed for the creation of drones as commonly intended for today's standards. For such reasons, the American MQ-1 Predator by General Atomics is certainly a milestone in drones' history and could be considered the first of contemporary drones. Presented to the public in 1995 and used mainly by the United States Air Force and CIA, the Predator has a wingspan of almost 15 meters, can fly at a speed of 130-165 km/h with a range of 1'100 kilometers circa and is equipped with cameras and other advanced reconnaissance systems[207]. Moreover, it can carry and fire missiles such as the anti-tank air-to-ground 114 Hellfire. Remotedly piloted, Predators have been used in Afghanistan, Pakistan, Bosnia, Serbia, Iraq, Yemen, Libya, Syria and Somalia, mainly for border reinforcement and anti-terrorism operations. Some units have been lost due to the harsh weather, operator errors or equipment failure, while other have been shot down by enemy fire,

[206] Imperial Drone Museum, "A Brief History of Drones", iwm.org.uk, iwm.org.uk/history/a-brief-history-of-drones

[207] Bart Custers, "The Future of Drone Usage: Opportunities and Threats from Ethical and Legal Perspective", Information technology and Law Series, Asser Press, 1996

like in Syria[208], or by a MiG-25 jet and some SAMs like in Iraq[209], proving that modern drones still had major room for future implementations. Nonetheless, it is believed that the counter-terrorism operations carried on by the United States on Afghani and Pakistani soil has been a clear bolsterer for drones employment. Despite having faced a reluctant public opinion, which protested against the imprecision of some drone strikes resulting in civilian deaths, their deployment has been related to an overall decrease in "the incidence and lethality of terrorist attacks, as well as decreases in particularly intimidating and deadly terrorist tactics"[210].

Because of that, new, more advanced, versions of the Predator were developed. In February 2007, the MQ-9 Reaper, also known as Predator-B, entered service in the United States Air Force. The Reaper can be considered the first true combat drone, featuring bigger dimensions that allow the drone to improve the Predator's already impressive characteristics. The Reaper shows a turbine engine very similar to planes' ones which, developing more power, allow the drone to carry up to fifteen times more ordinance payload than its predecessor and has a cruise speed about three times faster than the Predators[211]. In order to improve MQ-9's saliency, General Atomics has designed this drone to be remotely piloted with the same ground stations that can operate MQ-1s as well. Perhaps, one of the most relevant milestones for drones' history achieved by the Reaper was not about performance and lethality. Indeed, in 2008, the whole 174th Attack Wing unit for the New York National Guard was the first to experience a radical shift under drones' growing influence, transitioning from a squadron of F-16 fighters to a fleet composed entirely by Reapers UCAV. The decision, apparently, was taken in order to keep the Hancock Air Ground Base operative for the upcoming years, providing

[208] Brian Everstine, "Air Force: Lost Predator was shot down in Syria", AirForceTimes, 2015, airforcetimes.com/news/pentagon-congress/2015/06/29/air-force-lost-predator-was-shot-down-in-syria/
[209] Michael Knights, "Cradle of Conflict: Iraq and the birth of Modern U.S. Military Power", Naval Institute Press, 2005
[210] Patrick B. Johnson and Anoop K. Sarbahi, "The Impact of US Drone Strikes on Terrorism in Pakistan", International Studies Quartely, Vol. 60, 2016
[211] U.S. Air Force, "Reaper moniker given to MQ-9 unmanned aerial vehicle", af.mil, //www.af.mil/news/story.asp?storyID=123027012

training for unmanned vehicles piloting[212]. However, the Reaper had chances to prove its unquestioned lethality as well during its time in service. In 2022, the MQ-9 was protagonist in what is considered to be one of the most well-executed drone strikes in history. In Kabul, an MQ-9 Reaper launched two Hellfire missiles against the safehouse of al-Qaeda's leader al-Zawahiri[213], killing him in the process. Such operation has been considered of crucial interest for future drone employment by researchers, since it illustrates how drones could possibly allow nation-states to execute intelligence and counter-terrorism missions without having to deploy special forces and intelligence directly on the ground, hinting at the possibility to operate even beyond the farthest horizon with reduced costs[214].

Lastly, a third version of the Predator has been recently developed by the United States Air Force, the MQ-20 Predator C Avenger drone. Now operationally ready, the Avenger perfectly shows what could possibly be drones' trends for the upcoming years, possessing integrated stealth design features, such as the internal bay for weaponry and an S-shaped exhaust, to reduce radar as well as infrared traces[215]. Moreover, the MQ-20 was equipped with synthetic-aperture reconnaissance radar, capable of recreating 3-D reconstruction of battlefields, and a version of the F-35's electro-optical targeting system[216], showing how enormous steps forward have been made in the amount of data that the

[212] Cap. Anthony L. Bucci, " The Year in Review: Looking back on 2010 at Hancock Field Air National Ground Base", 174attackwing.ang.af.mil, 2010, 174attackwing.ang.af.mil/News/Article-Display/Article/439406/the-year-in-review-looking-back-on-2010-at-hancock-field-air-national-guard-base/

[213] MQ-9's employment cannot be confirmed by official sources, nonetheless experts coherently suggest its deployment in the strike mission. For further details, see Stefano D'Urso, "Al-Qaeda Leader Ayman al-Zawahiri Killed in US Drone Strike. Here's Everything We Know.", The Aviationist, 2022, theaviationist.com/2022/08/02/al-qaeda-leader-ayman-al-zawahiri-killed-in-us-drone-strike-heres-everything-we-know/; Shane Harris, Dan Lamothe, Karen DeYoung, Souad Mekhennet and Pamela Constable, "U.S. kills al-Qaeda leader Ayman al-Zawahiri in drone strike in Kabul", The Washington Post, 2022, washingtonpost.com/national-security/2022/08/01/zawahiri-al-qaeda-killed/

[214] Aaron David Miller, "What the Al-Qaeda Drone Strike reveals About U.S. Strategy in Afghanistan", Carnegie Endowment for International Peace, 2022, carnegieendowment.org/2022/08/02/what-al-qaeda-drone-strike-reveals-about-u.s.-strategy-in-afghanistan-pub-87616

[215] David A. Fulghum and Bill Sweetman, "New Predator C Hints at Stealth, Weaponry", Aviation Week, 2009, aviationweek.com/aw/generic/story_channel.jsp?channel=defense&id=news%2FAVENGE041509.xml

[216] General Atomics Aeronautical Systems, "GA-ASI Successfully Executes First Flight of Predator C Avenger", 2009, www.ga-asi.com/news_events/index.php?read=1&id=186

Avenger can cope with in real time. Deployed in Afghanistan[217], the MQ-20 embodies a conception of drones very similar to war planes but without an aircrew, a feature allowing it to possibly operate even in the most dangerous and defended environments without putting in danger any operator.

Nonetheless, it is important to remark that drones could actually come in very different versions, all ready to accommodate different requirements. Given the fact that hardwares are becoming more powerful but shrinking in size[218], drones of all shapes and dimensions can potentially be developed, in order for them to accomplish more and more specific tasks. Drones' portfolio currently includes an extremely wide spectrum of models, starting from bigger and stealthy remotely piloted ones such as the MQ-20 up to hand-portable autonomous targeting-acquiring DefendTex D40 Kamikaze ones[219] which self-explodes when striking their target. Only the future will tell where the limits of drone development are settled, considering also the ethical, legal and strategic complications that arise when wars are possibly fought by machines only.

5.2 Drones Tactics and Deployment

As previously stated in the introduction, very different UCAVs currently exist and their specifics reflect the operational requirements that each model must pursue, even though most of them show some impressive flexibility, a feature which furthermore enhances their military salience[220]. Nonetheless, there are different parameters that may help to understand drones' deployment while addressing their specific roles in the military.

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[217] David Axe, "New Armed Stealth Drone Heads to Afghanistan (and Maybe Iran, too)", Wired, 2011, wired.com/2011/12/stealth-drone-afghanistan/

[218] Frank J. Bartos, "Shrinking Hardwares, Increasing Functions", Control Engineering, 2004, controleng.com/articles/shrinking-hardware-increasing-functions/

[219] Military Leak, "Australia to Deliver 300 DefendTex D40 Kamikaze Drones to Ukraine", MilitaryLeak.com, militaryleak.com/2022/08/26/australia-to-deliver-300-defendtex-d40-kamikaze-drones-to-ukrainia/

[220] Andrea Gilli and Mauro Gilli, "The Diffusion of Drone Warfare? Industrial, Organizational and Infrastructural Constraints: Military Innovations and the Ecosystem Challenge", Security Studies Volume 25, 2016

First of all, UCAVs of any category do not include the possibility to have an aircrew on board. This characteristic alone may be one of the most revolutionary features recently introduced by drones in the military domain: drones replace human presence on ground, so that no "allied" human lives are at direct stake. Indeed, operating only under real-time human control or through their own computerized autonomy, drones can execute strike, intelligence, surveillance and reconnaissance tasks principally[221]. Their true potential, however, lies in avoiding risks for the operator. This is indeed a huge deal for militaries. Armies spend enormous amounts of time and resources to train and prepare their units to fight and properly operate vehicles. If some personnel get lost, new units must endure all the training that their predecessor went through to keep up to the armed forces' high standards[222]. With war becoming a more and more specific sector with almost endless facets, considering soldiers expendables is a wrong assumption for both ethical and strategic means. This is particularly true for air force pilots, since their training is considered one of the most costly and long-going to accomplish due to simulations, general training and flight hours[223].

Behind nations' growing interest toward drone technology, however, there are many other elements for such consistent appeal. In particular, intelligence gathering and surveillance seems to be the ones that meet the most infantry's needs on the battlefield. Drone can indeed be used to collect different parameters of information even in the most harsh environments, considering not only the enemy's presence but even the battle scenario itself. For example, in a context of urban conflict, traditional reconnaissance tools may face quite some trouble to shed light into the almost infinite concealment spots that the metropolitan environment has to offer[224]. Because of that, drones, with

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[221] *Ibis*.

[222] Sean Kimmons, "OPAT reducing trainee attrition, avoiding millions in wasted training dollars, officials says", U.S. Army, 2018, army.mil/article/207956/opat_reducing_trainee_attrition_avoiding_millions_in_wasted_training_dollars_officials_say

[223] Niall McArthy, "The Cost of Training Air Force Fighters Pilots", Forbes, 2019, forbes.com/sites/niallmccarthy/2019/04/09/the-cost-of-training-u-s-air-force-fighter-pilots-infographic/?sh=4768db9f7973

[224] Tanmay Kadam, "Used by Elite Indian Commando, Ukraine to receive 850 Black Hornet Micro Drones to Penetrate Russian Defenses", The EurAsian Times, 2022, eurasiantimes.com/commandos-ukraine-to-receive-850-black-hornet-micro-drones/

their reduced dimensions and inferior operative requirements, could actually operate in such a setting and provide support for reconnaissance as well as strike in one single package[225], even if an infantry unit may not be able to order an airstrike with traditional communication tools, a feature enhancing its force package considerably.

Overall, it could be stated that drones' deployment is not going to diminish in the upcoming years. Drones, indeed, provide a series of tactical benefits such as intelligence support and strike capabilities which will always come in handy on the battlefield nowadays and are only going to be even more crucial in the future. Their actual influence on the outcome of contemporary clashes, however, is not clear. Drones allegedly help to level the field between the fighting parts and the early stages of Russia-Ukraine conflict seems to support such a thesis, with Moscow's personnel facing perpetuous challenges despite facing an endlessly inferior military. Nonetheless other extremely important variables, such as the NATO Western support, may be the ones responsible for Russia's current difficulties and drones may just be the tip of the iceberg. What appears to be more evident, is that drones have all the possibilities to fit in the extremely lethal air warfare modern system of force employment, characterized by the mantra "what we see we can hit; what we hit we can kill"[226], which means that the most effective tools for contemporary air conflicts are the ones capable of hiding from enemy sensors while looking for targets to strike[227]. Drones seem to adapt adequately in these unforgiving conditions and apparently have better chances of eluding conventional detection systems, making them formidable military tools under the right circumstances: their lethality is indeed nothing to be underestimated[228].

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[225] Antonio Calcara, Andrea Gilli, Mauro Gilli, Raffaele Marchetti and Ivan Zaccagni, "The Drone Revolution in Military Affairs? Understanding the Hider-Finder Competition in Air Warfare", International Security Volume 46, Issue 4, MIT Press, 2022

[226] Dwight E. Phillips Jr., "Reengineering Institutional Culture and American Way of War in the Post-Vietnam U.S. Army, 1968-1989", University of Chicago, 2014

[227] Heilenday Frank, "Principles of Air Defense and Air Vehicle Penetration", Defense Technical Information Center, 2000

[228] T. X. Hammes, "Droning America: The Tech our Enemies Can Buy", War on the Rocks, 2013, warontherocks.com/2013/10/droning-america-the-tech-our-enemies-can-buy/

However, it is true as well that drones have collected different outcomes through their deployment in battlefields over the last decade. If their impact on the Russia-Ukraine war has been quite positive[229], it is remarkable to remember that drones have also faced troubles in previous clashes, which often resulted in their presence being far from determinant for the final outcome. For example, in the 2019-2020 Western Libyan Campaign, drones could not penetrate air defense systems as easily as it was believed and in the end provided little, if none, support to the armies they were deployed for. The Libyan National Army lost 9-to-11 drones out of the 20-30 units it had at disposition, while the Government of National Accord lost 22 out of its 24 drones during operations[230]. The causes of such underperformance are to be linked with ground-fired missiles used by both factions[231] which met few challenges in locking and then firing at their quarry. Quoting Italians experts and researchers "attrition rates among combat drones strongly correlate with the presence and capabilities of the air-defense systems deployed by the enemy"[232]. This means that not only drones were not able to elude conventional air-defense systems, but that they had been easy targets as well: the believed overwhelming capabilities of UCAVs simply did not find any confirmation during the Libyan conflict.

Considering all that was written before, in the end, it seems clear that addressing the consequences of drones' deployment and tactics in military affairs is a tricky task at last, involving a great number of variables which may indeed lead to precarious assumptions. Moreover, experts share consistently different evaluations about the topic among each other and empirical searches are going to become more and more crucial for scholars investigating the factual repercussions of combat drones

[229] Ragip Solyu, "Ukraine Received 50 Turkish Bayraktar TB2s Drones Since Russian Invasion", Middle East Eye, 2022, middleeasteye.net/news/russia-ukraine-war-tb2-bayraktar-drones-fifty-received

[230] Drone Crash Database, last updated August 31, 2022, dronewars.net/drone-crash-database/

[231] Franz-Stefan Gady, "Useful, but not decisive: UAVs in Libya's Civil War", The International institute for Strategic Studies, 2019, iiss.org/blogs/analysis/2019/11/mide-uavs-in-libyas-civil-war

[232] Antonio Calcara, Andrea Gilli, Mauro Gilli, Raffaele Marchetti and Ivan Zaccagni, "The Drone Revolution in Military Affairs? Understanding the Hider-Finder Competition in Air Warfare", International Security Volume 46, Issue 4, MIT Press, 2022

deployment. So, in order to present a more clear picture of such a topic, the following chapter will present some critics regarding the supposed drones' crucial and revolutionary role in the contemporary military presented by traditional international relations' literature, with a deep look at what might actually come next in the future.

5.3 Drones' Revolution in Military Affairs?

The title of this chapter is taken from a notable paper written by a team of Italians experts and researchers of military technology composed by Antonio Calcara, Andrea Gilli, Mauro Gilli, Raffaele Marchetti and Ivan Zaccagni. The authors wanted to address, through empirical investigation, if the drone revolution in military affairs is actually taking place and if the alarms flagged by the international relations community are based on factual events. A deep look at what their work provided should definitely be helpful in the comparison of offensive advantage between drones and last generation stealth fighter jets that this paper proposes.

According to drone revolution supporters, drones inherently possess three main characteristics that will lead to them overtaking the military domain, with heavy repercussions on the ethical, strategic and legal aspect as well as the whole distribution of power around the world. The first feature is about the offense-defense balance. Quoting the paper, "drones yield an offensive advantage because they can penetrate enemy's air defense systems [...] because of their small size and other physical features, drones are difficult to detect and track for modern air defense systems". Moreover, "drones' cheap costs permit actors to employ them in large numbers and thus to saturate (overwhelm) enemy's air defense systems". If such a theory would be correct, we would witness drones face little if not zero attrition when invading enemy's skies in recent conflicts, with defensive systems being not able to cope with their peculiar features and/or overwhelming quantities. However, some cases prove this thesis to be not correct, at least in absolute terms. Adding to the previously quoted case of the Western Libyan Campaign in chapter 5.2, the Syrian Civil War, which started in 2011, presents some similar

patterns which led drones to experience extended attrition rate, which later on resulted in their deployment being mostly uneffective. Despite being "the most drone-dense conflict to date"[233], drones were eventually "dropping like flies from the sky"[234], hinting how their supposed offensive superiority was not finding any fact-based feedback. Russian air defense systems were indeed able to counter and neutralize most drone threats, thanks to a combination of short-ranged weaponry merged with the specialists' experience of the Russian electronic warfare units. Between 2018 and 2020, in the second phase of the civil war, over 150 drones were disabled by Russia and, in 2019 alone, around 60 multiple drones, as well as missile, attacks against its Khmeimim air base were successfully counteracted[235]. Even if Russia's air defenses were not always effective, this was more related with force employment and coordination rather than the revolutionary nature of drones, according to the experts.

The second crucial as well as revolutionary attribute held by drones, based on the drone revolution thesis, is that they may alter the distribution of power, favoring a consistent leveling effect among nations' armed forces. Quoting the Italian experts "since drones are easy to produce, cheap to procure and easy to employ, they are going to strengthen weaker actors, thus exerting a leveling effect on international politics [...] the weaker side is more likely to rely on drones [...] especially when facing significantly stronger adversaries". However, as the paper underlines, different recent conflicts actually prove that is the stronger side to gain the most benefits from drones' employment. For example, in the 2020 Azerbaijan-Armenian conflict over the region of Nagorno-Karabakh, also known as the "44 days war", drones systematically supported and favored the stronger faction, which in this case was Azerbaijan. In fact, Baku invested a growing amount of resources into its defense spending in the two years preceding the conflict and was outspending by 3 times circa the whole

[233] Dan Gettinger, "Drones Operating in Syria and Iraq", Center for the Study of the Drone, Bard College, 2016

[234] Tom Cooper, "Drones are Dropping Like Flies from the Sky Over Syria. Shoot down are becoming commonplace", War is Boring, 2017, warisboring.com/drones-are-dropping-like-flies-from-the-sky-over-syria/

[235] Sameeer Joshi, "Drone Swarms: The Next Evolution in Warfare", Raksha Anirveda, 2021, raksha-anirveda.com/drone-swarms-the-next-evolution-in-warfare/

defense budget of Armenia[236]. Moreover, Azerbaijan received support from a powerful actor such as Turkey, which almost forced themselves into the conflict to run the drone campaign against Armenia[237]. In the end, Armenia was not only the weaker part of the conflict but did not receive any kind of support from external actors. Finding itself in the conditions that allegedly would have most favored a huge deployment of drones, as the paper points out, "Armenia did not turn to drones to redress its numerical and qualitative inferiority". This conflict also proves another point of the drone revolution wrong: drones are not cheap and effective in absolute terms. Indeed, Azerbaijan, with its immense defense spending compared to its opponent, was able to acquire a huge foreign-manufactured drones fleet, including some Turkish Bayraktar TB-2s and Israeli Hermes-900s[238], while Armenia only had at its disposal some loitering munitions with few Russian-made UAVs Orlan-10[239]. Because of that, Armenia turned to ballistic missiles against Azerbaijan as a weapon of last resort, and not drones as the revolution-related thesis would have instead suggested[240].

Lastly, the third and final subversive trait possessed by drones, as it is presented by the drone-revolution supporters, is about their capability to make close infantry combat obsolete, changing forever strategies and protocols of force employment. Quoting the Italian researchers team "Drones are thought to permit unrestrained long-range precision-strikes that can destroy, at will, any intended target". Furtherly, as a consequence, "employment of drones should make ground combat unnecessary" in order to win battles. As the team points out, however, this is not the case and, in order to sustain their observations, provide further details of the previously quoted three conflict scenarios, where drones did not even hint at taking over ground combat despite the apparently favorable conditions for doing so. The Libyan Civil War, despite the employment of drones by both the Libyan

[236] SIPRI, Sipri Military Expenditure Database, sipri.org

[237] Tatevik Hayrapetyan, "How Ilham 'Personalizes' the Results of the 2020 Artsakh War", ENV Report, 2021, evnreport.com/politics/how-ilham-aliyev-personalizes-the-results-of-the-2020-artsakh-war/

[238] Burak Ege Bekdil, "Azerbaijan to Buy Armed Drones from Turkey", Defense News, 2020, defensenews.com/unmanned/2020/06/25/azerbaijan-to-buy-armed-drones-from-turkey/

[239] International Institute for Strategic Studies, "The Military Balance 2020",

[240] Shaikh and Rumbaugh, "The Air Missile War in Nagorno-Karabakh"

National Army and the Government of National Accord, has not witnessed the disappearance of close combat. Indeed, both the parts relied on infantry units, beside artillery and airpower, to take control of crucial infrastructures such as airports, highways and crossroads. To furtherly prove the importance of ground-based soldiers, both the LNA and the GNA hired mercenaries to defend strategic positions and execute mopping-up operations[241]. Turkey's support toward the GNA was crucial and furthermore proved how combat skills and traditional force employment have not lost relevance. Turkish specialists were indeed able to end LNA's air while allowing GNA's forces to counterattack and put an end to the siege of Tripoli[242]. Turkey's crucial intervention was not granted only by drones, but by a mix of artillery, radar systems and general organizational and infrastructural support. Drones alone would have not been able to turn the tide of the siege of Tripoli.

The Syrian Drone War provides us with more variables that seem to undermine the believed strategic decay of infantry combat promoted by drones. Despite their supposed low costs and high effectiveness, it is to wonder why the Syrian armed forces, along with their Iranian and Russian supporters, opted for relying heavily on standoff fire through artillery, attack helicopters and air-to-ground bombers, which are consistently more expensive alternatives[243]. Moreover, the limited experience and relatively poor skills of the Syrian military personnel at operating air-defense systems exposed their position to enemy fire, which indeed looks to be the most rational cause to explain the initial success that drones faced when destroying Russian-manufactured long-range anti-air systems[244]. On the other side, the Syrian Government's adversaries proved to be remarkably more proficient in the suppression of air-defenses. This furtherly proves how combat experience and on-

[241] Jason Pack and Wolfgang Pusztai, "Turning the Tide: How Turkey Won the War in Tripoli", Middle East Institute, 2020

[242] Itamildar, "Turkish 'Hawk' Deployed in Tripoli", Italmidar, 2020, itamilradar.com/2020/01/18/turkish-hawk-deployed-in-tripoli/

[243] Ralph Schield, "Russian AirPower's Success in Syria: Assessing Evolution in Kinetic Counterinsurgencies", Journal of Slavic and Military Studies, Vol.31, No.2, 2018; Timothy Thomas, "Russian Lessons Learned in Syria: An Assessment", MITRE, 2020

[244] John V. Parachini and Peter A. Wilson, "Drone-Era Warfare Shows the Operational Limits of Air Defense Systems", RAND Corporation, 2020, rand.org/blog/2020/07/drone-era-warfare-shows-the-operational-limits-of-air.html

ground operators can actually make a great difference for the conflict's outcome, proving how unlikely it is for these capabilities to become less relevant in the upcoming years, and even less likely for them to be replaced by drone employment.

The Nagorno-Karabakh conflict provides us additional proofs leading to the conclusion that close combat, as well as on-ground clashes, are far from disappearing and, in this scenario in particular, was even more crucial than usual. Indeed, despite the employment of loitering munitions, ballistic missiles and other precision-guided munitions, infantry units proved to be pivotal on the battlefield both for defensive as well as offensive purposes[245]. In particular, according to some, the deployment of Syrian mercenaries from Turkey in favor of Azerbaijan was a real game-changer: operating in coordination with other elements of the armed forces, mercenaries helped to overwhelm Armenian forces by an order of magnitude and in the end forced Russia to intervene on a diplomatic level[246]. With Azeri armed forces relying extensively on exploiting the morphology of the territory at their advantage, they were able to limit their exposure to radars and hence minimize the risk of interception while effectively suppressing Armenian air defenses[247]. Moreover, Azeri drones were found impossible to be deployed in peculiar battle scenario of Shusha City due to foggy weather conditions, allowing the 2'000 Armenian troops to maximize the usage of T-72 tanks which would have been otherwise priority targets for drone-strikes[248]. In conclusion, even in the Azerbaijan-Armenia conflict, drones were not able to delete ground combat or to erase distance between targets, and even proved themselves unreliable under certain weather conditions.

Lastly, the ongoing conflict between Russia and Ukraine provides some insights about drones' role in the most recent conflict Europe experienced. Once again, different empirical circumstances

[245] Bethan McKernan, "Trench warfare, drones and cowering civilians: on the ground in Nagorno-Karabakh", The Guardian, 2020, theguardian.com/artanddesign/2020/oct/13/trench-warfare-drones-and-cowering-civilians-on-the-ground-in-nagorno-karabakh

[246] Miron and Thorton, "Russia's 'revenge' after Nagorno-Karabakh"

[247] Kofman and Nersisyan, "The Second Nagorno-Karabakh War"

[248] Spencer and Ghoorhoo, "The Battle of Shusha City"

seem to prove the drone revolution hypothesis wrong for most aspects. First of all, drones are not shown to be easy to manufacture. Kiev's native drone fleet would have never been capable of holding against an immense army as the Russian one. The resistance had to employ drones which were neither its property nor Ukrainian-manufactured, but were given instead by supporting foreign countries such as Turkey[249]. Even Moscow itself seems to have received some combat-specific UCAV from Iran[250]. If drones were so easy to build, it would have been wise to expect an immense domestic peak in drones' production for both factions, an event which, however, never occurred. Nonetheless, unmanned aerial vehicles showed considerable results in dealing with Russian armored vehicles in the early stages of the war but, remarkable lacks of the Russian military's supply chain and an imprecise mission planning, may have fueled drones' lethality considerably in the short run[251]. In fact, as Russia's operation kept going, its military was able to shrink down drones' threat substantially[252]. Indeed, it would be wrong to consider drones as the key element keeping the Ukrainian resistance safe from defeat and for sure drones have not favored the weaker side enough to consider their employment as revolutionary. Drones were also proved to be not invulnerable to traditional anti-aerial systems, as the theory otherwise suggests, and numerous of them, belonging to both factions, have been shot down now that the military personnels are better prepared to face them[253]. Overall, it could be stated that drones have not revolutionized the force-balance of the fighting factions but, for sure, their role is acquiring more saliency also due to the kind of conflict Russian and Ukraine are experiencing. Fighting on huge flat lands that provide very few chances of concealment or successful ground-driven attacks, artillery is the main driving force of the war and

[249] BBC News, "Ukraine conflict: How are drones being used?", 2022, bbc.com/news/world-62225830

[250] Ellen Nakashima and Joby Warrick, "Iran sends first of drones to Russia for use in Ukraine", The Washington Post, 2022, washingtonpost.com/national-security/2022/08/29/iran-drones-russia-ukraine-war/

[251] Stephen Witt, "The Turkish Drone That Changed The Nature of Warfare", The New Yorker, 2022, newyorker.com/magazine/2022/05/16/the-turkish-drone-that-changed-the-nature-of-warfare

[252] David Axe, "After Five Months Russia Finally Managed to Destroy Some Ukrainian Drone Equipment", Forbes, 2022, forbes.com/sites/davidaxe/2022/07/28/after-five-months-the-russians-finally-managed-to-destroy-some-ukrainian-drone-equipment/?sh=40f4db7a1aea

[253] Oryx Database, last seen September 2022, oryxspioenkop.com/2022/02/attack-on-europe-documenting-equipment.html

one of the Russian's army backbones[254]. With both factions shielding under strategic points and using long-range systems to hit each other, drones are basically providing an alternative for some precision strikes that, despite the lethality, are not likely to be crucial for the final outcome of the conflict but can for sure buy some more time against Moscow's army, forcing it to spend more and more resources in order to drag on the invasion[255].

5.4 Drones and Stealth

Traditionally, drones are believed to inherently possess features that help them to elude radar tracking[256]. These characteristics reside, first of all, in most drones' reduced dimensions: the smaller the aircraft, the less chances there are for radar radio waves to bounce back to the receiving antenna, resulting in the UCAV possibly being spotted but not necessarily being automatically tracked. Moreover, their smaller engines, compared to traditional manned aircrafts, makes it also difficult for infrared-technology-reliant MANPADs or heat-seeking missiles to lock-on and fire at drones. Overall, stealthy drones follow the same principles for pursuing stealth that fighter and bombers do, with their hard-body shaped designed to reflect radar waves and other shrednesses to avoid leaving track-exploiting traces such as, for example, heat. Moreover drones, being remotely-piloted, face poor means of defense in case of engagement: because of that, stealth is the most consistent key feature for assuring UCAVs' and UAVs' survivability, since they do not possess the capabilities to defend themselves against enemy fire, the agility to elude incoming attacks or even the speed to escape. However, without the need of an aircrew, drones' stealthy frameworks may actually overtake

[254] Illia Ponomarenko, "Why Ukraine struggles to fight Russia's artillery superiority", The Kyiv Independent, 2022, kyivindependent.com/national/why-ukraine-struggles-to-combat-russias-artillery-superiority
[255] Joe Gould, "US weapons package for Ukraine stresses long-haul commitment", Defense News, 2022, defensenews.com/pentagon/2022/08/24/us-to-send-ukraine-anti-air-anti-drone-systems-as-war-hits-milestone/
[256] Antonio Calcara, Andrea Gilli, Mauro Gilli, Raffaele Marchetti and Ivan Zaccagni, "The Drone Revolution in Military Affairs? Understanding the Hider-Finder Competition in Air Warfare", International Security Volume 46, Issue 4, MIT Press, 2022

notorious weak-points of manned stealth vehicles such as the canopy, for example, theoretically leaving room for new and improved Radar Cross Section capabilities to be sharpened in the future.

Considering however that reduced dimensions translate into shrinked operational capabilities, such as operative and cruising range, the next step in drones' evolution seems to be more inclined to favor the development of larger and larger unmanned combat air vehicles, in order to overcome the previously quoted limitations. Nonetheless, given the lethality that air domain presents nowadays, a larger aircraft will always need some kind of advanced stealth capabilities in order to grant its survivability against air defense systems, A2-AD apparatuses and enemy drones or fighters. At a first glimpse, the Lock-Heed Martin RQ-170 Sentinel seems to be the drone that most accommodates these requirements. Designed to be a reconnaissance UAV with a wingspan of about 20 meters, its framework shows remarkable similarities with the Polecat model drones, featuring flat and smooth surfaces, tailless flying wings body and probably some radar absorbing materials[257] over the "skin". In order to maximize its stealth capabilities as well as its survivability, Lock-Heed decided to not equip it with any weaponry, designating the Sentinel to a service of pure intelligence gathering for the United States Air Force[258]. In order to accomplish such task, the drone has been equipped with an AESA radar and electro-optical as well as infrared sensors[259]. The New York Times even speculated that the RQ-170 may be stocked with particular chemical sensors capable of detecting even small amounts of radioactive isotopes, which are used to indicate the possible existence of nuclear facilities

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[257] David A. Fulghum, "RQ-170 Has Links To Intelligence Loss to China", Aviation Week, 2009, web.archive.org/web/20121016142710/http://www.aviationweek.com/Blogs.aspx?plckBlogId=Blog:27ec4a53-dcc8-42d0-bd3a-01329aef79a7&plckController=Blog&plckBlogPage=BlogViewPost&newspaperUserId=27ec4a53-dcc8-42d0-bd3a-01329aef79a7&plckPostId=Blog:27ec4a53-dcc8-42d0-bd3a-01329aef79a7Post:7544751e-3bdc-4e52-9be7-07000988da92&plckScript=blogScript&plckElementId=blogDest

[258] David A. Fulghum, "U.S. AirForce Reveals Operational Stealth UAV", Aviation Week, 2009, web.archive.org/web/20111117090945/http://www.aviationweek.com/aw/blogs/defense/index.jsp?plckController=Blog&plckBlogPage=BlogViewPost&newspaperUserId=27ec4a53-dcc8-42d0-bd3a-01329aef79a7&plckPostId=Blog%3a27ec4a53-dcc8-42d0-bd3a-01329aef79a7Post%3a649e3cf4-8c07-4739-82cf-322c6c56ccd5&plckScript=blogScript&plckElementId=blogDest

[259] Bill Sweetman, "The Beast is Back", Aviation Week, 2011, https://web.archive.org/web/20111117085419/http://www.aviationweek.com/aw/blogs/defense/index.jsp?plckController=Blog&plckBlogPage=BlogViewPost&newspaperUserId=27ec4a53-dcc8-42d0-bd3a-01329aef79a7&plckPostId=Blog%3a27ec4a53-dcc8-42d0-bd3a-01329aef79a7Post%3a5b32f70f-3054-4261-947e-dc8fe095d08b&plckScript=blogScript&plckElementId=blogDest

in non-friendly countries like Iran[260]. Very little official information is currently available to the public: Lock-Heed Martin's official website only presents some extremely vague descriptions about company's drones projects currently under development, with the RQ-170 Sentinel not being even properly mentioned[261]. In fact, most of what was reported before is mainly up to experts' speculations: for example, pretty much nothing is known about Sentinel's engine but, considering the recent trends in stealth and drone technology, integrated with the drone's specific role for reconnaissance, it would be wise to expect the RQ-170's motor to release extremely limited heat traces[262], while its buried positioning resembles the B-2 Spirit bomber's engines and should enhance radar concealment.

Regarding combat-specific drones, stealth capabilities are fundamental for such models as well. As it has been described in previous chapters, stealth is an extremely viable resource for offensive purposes as well, capable of forcing the defenders into a detection challenge that even the most experienced personnel, equipped with advanced air defense systems, may not be able to win. The British Manufactured BAE Systems Taranis UCAV seems to present some peculiar features developed for combat-focused stealth drones: a stealthy hard-body shaping with two internal bays for weaponry, an estimated maximum take-off load capability of over 8'000 kilograms[263] and advanced autonomy proficiencies, which allow the Taranis to be employed in long-lasting missions without the need of a remote human operator for the most of the time[264]. Once again, however, there is very little confirmable information and BAE Systems itself seems to grant maximum secrecy about the drone, probably due to its ongoing development phase and the strategic potential which it inherently possesses. The Taranis and BAE Systems have been crucial protagonists for UK defense policies,

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[260] Scott Shane and David E. Sanger, "Drone Crash in Iran Reveals Secret U.S Surveillance Effort", The New York Times, 2011, nytimes.com/2011/12/08/world/middleeast/drone-crash-in-iran-reveals-secret-us-surveillance-bid.html

[261] Lock-Heed Martin, ISR & Unmanned Systems, lockheedmartin.com/en-us/who-we-are/business-areas/aeronautics/skunkworks.html

[262] David Hambling, "Mysteries Surrounding Afghanistan's Stealth Drone (Updated)", Wired, 2009, wired.com/2009/12/mysteries-surround-afghanistans-stealth-drone/

[263] BAE Systems, www.baesystems.com/en-uk/product/taranis1

[264] Paul Marks, "Warning Sounded Over British Dogfighting Drone", New Scientist, 2010, newscientist.com/article/dn19162-warning-sounded-over-british-dogfighting-drone/?ignored=irrelevant

since the British Government wanted to maintain some kind of sovereignty over the know-how and constructional knowledge of nationally-manufactured UCAVs as well as UAVs, avoiding to simply buy drones from foreign countries[265]. For the upcoming decades, many combat drones' top priority to acquire and implement seems to be related to the field of artificial intelligence which, if properly developed, would allow such drones to detect and engage targets in complete autonomy, furtherly enhancing their fighting capabilities and their operational independence. How will an IA distinguish soldiers from civilians, however, is still unclear and remote human interaction, like the one provided by the MQ-series of American drones, seems to be best solution for contemporary factual deployment[266].

[265] Online News Room, "BAE Systems to lead £124 million UAV Technology Demonstration Programme", 2006, web.archive.org/web/20070613033420/http://147.29.80.132/newsroom/2006/dec/071206news1.htm

[266] Dan Sabbagh, Killer Drones: how many there are out there and who do they target?", The Guardian, 2019, theguardian.com/news/2019/nov/18/killer-drones-how-many-uav-predator-reaper

6. Comparing Offensive Advantage

6.1 Introduction to the comparison

Having considered the evolution, features, deployment and potentialities of both drones and 5th generation stealth fighters it is now time to compare these two vehicles' offensive advantage. The comparison will focus first on the crucial role of stealth for both counterparts and how such machines exploit it for mission accomplishment as well as for granting their own survivability. The comparison will consist of the two vehicles entering the same enemy territory completely alone, one at the time: their goal will be to strike a heavily-defended imaginary ground target. The parameter that will determine offensive advantage's evaluation will be the chances enemies have to take in order to execute the kill-chain, by trying to track and engage the intruder, or by sending fighters to intercept it. In order to get a broader picture of stealth fighters' and drones' offensive advantage, different elements such as speed, operational range, weapons load, and countermeasures capabilities will be taken into consideration as well in order to present a more reliable research.

The stealth fighter jet employed for the fictional mission will be a Lock-Heed Martin F-35 Lighting II, since its crucial role in the upcoming plans of US air dominance and defense have made it a centerpiece for contemporary and future Western air power. Moreover, the wide literature addressing F-35's strengths and flaws should be enough to accurately describe the jet's behaviors and capabilities during the strike operation.

For the drone counterpart, instead, the standards set by the F-35 will have to be at least equal to the fighter's ones. Indeed, if drones inherently possess a stronger offensive advantage, it should be possible to underline those capabilities by confronting the two parts carrying on the same mission. The American-manufactured MQ-9 Reaper capabilities will act as an exponent for the drones' side.

Indeed, the MQ-9 was chosen due to its recorded operations in countries such as Libya[267] and Kosovo[268], as well as its combat-specific features which make up for a perfect opponent to the F-35 in terms of possible offensive advantages. Moreover, the Reaper is considered by many to be the most advanced combat drone currently in full operational status, so it represent a perfect candidate to show contemporary drones' attack capabilities[269]. The overall comparison will also present interesting considerations that will sustain, or not, the supposed drone revolutions in military affairs currently taking place all around the globe, hoping to provide further elements for such debate.

The outcome of the confrontation will be described at the end of this chapter, while further considerations will be presented ahead in chapter 7.

6.2 F-35's offensive advantages

The mission gave the F-35 all the means to show its avenierstic features and top-of-the-notch equipment. First thing first, Lock-Heed Martin indicates the F-35's radius, in combat configuration, to be around 1'000 kilometers while its range surpasses 2'000 kilometers[270].These characteristics, merged with the F-35's predisposition to be re-fueled even while flying in mid-air[271], grants it almost unlimited range parameters. At the state of art, considering the established US military apparatus, there is virtually no place the F-35 cannot reach in full combat disposition. The single engine provides a top speed of Mach 1.6 (1960 km/h circa) but, according to some sources, some F-35 variants are

[267] Luca Peruzzi, "Italy flies first Predator B sortie over Libya", Flight Global, 2011, flightglobal.com/italy-flies-first-predator-b-sortie-over-libya/101538.article

[268] Cap. Roberto Berardi, "Kosovo: primo volo del Predator", Aeronautica Militare, 2012, web.archive.org/web/20150206223036/http://www.aeronautica.difesa.it/News/Pagine/KosovobattesimodelvolodelPredator.aspx

[269] Tom Sheve, "How the MQ-9 Reaper Works", HowStuffWorks, science.howstuffworks.com/reaper.htm

[270] Lock-Heed Martin, "Media Kit: F-35 A Information", lastly updated september 2022, f35.com/content/dam/lockheed-martin/aero/f35/documents/FG19-00608_001 Product Card F-35A media.pdf

[271] U.S. Air Force, "F-35 Refueling", 2013, af.mil/News/Photos/igphoto/2000048079/

not capable of holding such speed for long periods of time[272]. Nonetheless, a supersonic cruising speed of around 0,8 Mach should be enough to ensure the F-35 a rapid employment like few other fighters can. So, for the purpose of our imaginary mission, an interesting element arises already. Before the detection game can properly begin, and the offensive advantage being evaluated, one thing is already predominant: when given the authorization to take-off, the F-35 is able to reach mission's areas in extremely short times, a crucial characteristic for both offensive and defensive purposes. Even considering an eventual need for a mid-air refueling, such practice is unlikely to take more than 10 minutes with the so-called "Flying Boom" method[273], and so it is not expected to erode the F-35's overall speed and employment velocity. As our F-35 approaches the enemy's border, its stealthy body-shaping starts to show its potential, concealing the aircraft from enemy radar waves while coming at full speed towards the target. For our mission's objective, it is extremely likely to find our F-35 equipped with some kind of jamming device, in contemplation of reducing even more radar waves return[274]. Joining together stealth and jamming capabilities with high speed creates a lethal synergy extremely like to stress out even the most prepared defenders: even if some radar waves were to bounce back from the F-35 tail wings to the receiving antenna, the signal would be so blurry that enemies will have to question its the reliability while our fighter is running over the sky at around 1'000 km/h towards them. Generally, this is one of the phases most subject to endless variables but also where the F-35 has all the means to shine the most. In fact, F-35's huge versatility is granted by its extremely advanced data management capabilities, which allow it to overtake critical dangers such as eluding enemy radar stations, which may otherwise erode its stealthy upper hand depending on

[272] These problems have apparently been more critical for the B and C versions; Valerie Insinna and David B. Larter, "Supersonic speed could cause big problems for the F-35's stealth coating", Defense News, 2020, defensenews.com/air/2019/06/12/supersonic-speeds-could-cause-big-problems-for-the-f-35s-stealth-coating/

[273] Executive Flyers, "How Long Does It Take to Refuel a Plane?", 2022, executiveflyers.com/how-long-does-it-take-to-refuel-a-plane/

[274] In a real conflict scenario, it is extremely unlikely for such aircraft to operate in complete solitude; instead, it is more likely to find it operating with other F-35s or with some previous generation fighters providing different degrees of support as well as protection. Because of that, some kind of arrangements to enhance the aircraft's stealth, and so survivability, are expected to be implemented.

where they are dislocated around the area. Empowered by the Distributed Aperture System (DAS) platform, the F-35 is continuously co-linked with other military platforms like communication centers and satellite hubs, always processing and collecting battle scenario data[275] in a way that enhances its versatility as well as survivability by an order of magnitude: if ever believed to be in danger, the F-35 has all the means to recognize and react to hidden as well as upcoming threats[276], adjusting its mission plan even in real time. After surpassing the border and entering in the enemy's air space, time is a crucial factor for success, since the kill-chain may be started with great accuracy at any point by the ground defenders. So, the F-35 has to act as rapidly and efficiently as possible to properly execute its mission. The first key goal is to individuate the target and, in order to achieve such a task, our F-35 is equipped with last generation Active Electronically Scanned Array (AESA) radar. Through AESA's extreme performances granted by its different-frequencies pulses and multi-beams emissions[277], there are high chances for the target to be spotted up to a distance of 100 kilometers without compromising its radar concealment[278]. This allows our F-35 to avoid and alert those defensive systems, such as SAM batteries, which would logically be more densely disposed closer to the target. While AESA radar provides to our fighter the crucial capability to locate the target at a considerable distance, the F-35 can be equipped with a vast variety of weaponry in order to enhance its operational versatility and lethality. In this crucial phase, our fighter cannot afford to miss its target since any missed shots would critically compromise the fighter's concealment and probably accelerate the defender's kill-chain procedure. For the purposes of our mission, a glide bomb like the AGM-154 Joint Standoff Weapon should be exactly what our fighter needs: a precision-guided,

[275] Rich Abbott, "New Demonstration Shows F-35's Data Sharing Capability", Aviation Today, 2019, aviationtoday.com/2019/08/08/82484/

[276] Paul C. Cabellon, "Northrop Grumman Distributed Aperture System (DAS) for F-35 Demonstrates Ballistic Missile Defense Capabilities", Northrop Grumman, 2010, news.northropgrumman.com/news/releases/photo-release-northrop-grumman-distributed-aperture-system-das-for-f-35-demonstrates-ballistic-missile-defense-capabilities

[277] Jon Lake, "AESA does it… or does it?", Times Aerospace, timesaerospace.aero/features/defence/aesa-does-itor-does-it

[278] Shishir Gupta, "India develops AESA radar to make IAF more lethal", Hindustan Times, 2021, hindustantimes.com/india-news/iaf-to-showcase-use-of-indigenous-aesa-radar-101638924141445.html

medium-long range ammunition capable of granting maximum lethality for the enemy and best survivability to allied aircraft, due to its capability to lock targets from considerable distances[279]. The advanced data management that only the F-35 can provide would allow the AGM-154 to synergize even more with the information gathered by the plane itself, resulting in higher probabilities of a precise strike. Once the target is hit and destroyed, defenders for sure will be forced to some kind of reaction, possibly arming all of their anti-air systems and sending their fighters to search for our intruder in the area. Once again, F-35 stealth capabilities will come in handy. It could be possible for our fighter to appear sometimes on the radar, but tracking it in order to take it down will not be an easy task for both air and ground forces. At the same time, the powerful single engine would provide enough thrust to evade enemy's air space in a matter of minutes. If ever locked by ground-to-air missiles, other fighters or any different variety of threat, our F-35 has still a couple of aces up its sleeve to protect its survivability: a built-in 25 millimeters rotary cannon to engage upcoming threats[280], tactical flares to elude upcoming missiles[281] and top-of-the-notch maneuverability would allow our fighter to escape the enemy's threat area, with solid chances of coming back home safely.

6.3 F-35's offensive advantage flaws

Overall, the F-35 is undoubtedly an exceptional machine with consistent versatility options, which perfectly reflect the economical as well as political context where it originated from: a multi-role stealth aircraft equipped with only the best technologies that the Western world has conceived in decades, capable of merging performance, lethality and economic costs in a single formula that will hold the backbone of western air forces for the foreseeable future. Nonetheless, the F-35 is still not perfect in absolute terms and its offensive advantage still presents some considerable flaws. Stealth

[279] Military.com, "AGM-154 Standoff Weapon", military.com/equipment/agm-154-joint-standoff-weapon

[280] Peter Sociu, "Why Does the F-35 Stealth Fighter Need a Gun? One Word: History", The National Interest, 2021, nationalinterest.org/blog/buzz/why-does-f-35-stealth-fighter-need-gun-one-word-history-179562

[281] Daniel Patrascu, "Inverted F-35 Lighting Fires Flares for First Time in Public, Looks Ready for War", Autoevolution, 2021, autoevolution.com/news/inverted-f-35-lightning-fires-flares-for-first-time-in-public-looks-ready-for-war-173378.html

is a necessary requirement for contemporary military vehicles, which would otherwise be easy prey of defensive systems and SAMs, but this does not mean that F-35's radar concealment is going to be completely guaranteed during the missions. Indeed, the detection game involving stealth fighters and radar is an extremely complex challenge between the two, where countless variables, both strategic but also environmental, could determine a positive or a negative outcome for the actors involved. Indeed, in our fictional mission, the location of radar stations on enemy soil is a crucial variable: as it has been stated before, there are some parts of the F-35, like the tail wings, that are more vulnerable to detection but, nonetheless, needed for aircraft maneuverability requirements. Depending on where radar stations are to be found, some radar waves may bounce back to their respective receiving antenna, eroding the fighter's occultation and alerting the defenders. Stealth capabilities will however buy some crucial time to the F-35 before the enemy even realizes that its airspace has been actually violated. Moreover, it is very unlikely to perform this kind of missions without having first gathered huge amounts of information about radar sites location and our F-35 could follow a specific pathway to avoid the most defended sectors, exploiting its low RCS at full potential. Overall, the execution of the kill-chain will always be an extremely complex challenge to perform against an aircraft so fast and elusive as the F-35 is. Nonetheless, the F-35 requires extremely advanced coordination capabilities to operate and a strong, prepared and experienced military apparatus is necessary to properly employ this aircraft at its maximum capabilities. The training that all pilots must come through, moreover, is also another crucial variable that may directly affect F-35s offensive advantages. Nonetheless, the western world, and in particular the US Air Force, still holds a remarkable primacy in this determining aspect, with continuous implementations and improvements being added as time goes by and simulation technology advances[282]. Another crucial flaw is about the cyber and interconnected dimension that the F-35 embodies with futuristic data management and its communication hub capability. It could be possible that such advanced machines may be critically

[282] Lock-Heed Martin, "10 Ways the F-35 Simulator is Changing Pilot Training", 2021, .f35.com/f35/news-and-features/10-ways-the-f35-simulator-is-changing-pilot-training.html

vulnerable to electronic warfare tools or to some typology of cyber-attacks directed against the plane's systems. Whatever the case, it is very doubtful for such kind of attacks to completely black-out the plane and the pilot is very plausible to always have some degree of control over it. Lastly, the F-35 single engine is not capable of providing supercruise capabilities due to some alleged structural vulnerabilities that would otherwise stress the aircraft too critically[283]. This is more of an engineering limit rather than a flaw, since all other known stealth fighters capable of supercruise have two separate engines, which however imply higher costs of construction, manutency and operativity as well as fuel consumption; elements that the F-35 was forced to compromise with since the beginning. Nonetheless, the F-35's afterburner can still be used for short periods of time, more than enough for effectively perform extreme maneuvers in dogfighting scenarios.

6.4 Drones' offensive advantage

At the very beginning of our mission plan, there are already a couple of remarkable elements to underline, in particular regarding speed and operational range. The US Air Force web site reports the MQ-9's operational range to be between 1'150 miles (1850 kilometers circa) and 1'600 miles (2574 kilometers circa)[284]. This grants considerable employment capabilities for drones. However, two things are to be considered. First, it is the drones' speed, which is far inferior compared to the supersonic one that a fighter jet can reach. The MQ-9 has a top speed of around 450 km/h, which of course translates into less fuel consumption and then into a wider range operativity. However, speed is a crucial factor for both offensive as well as defensive purposes and an incoming drone will actually have to take more time than a fighter jet to reach the designated area, look for the target and then escape. Whatever the case, drones' piloting autonomy may indeed overcome such inferiority, with

[283] David B. Larter and Valerie Insinna, "The Pentagon will have to live with limits on F-35's supersonic flights", Defense News, 2020, defensenews.com/air/2020/04/24/the-pentagon-will-have-to-live-with-limits-on-f-35s-supersonic-flights/

[284] US Air Force, "MQ-9 Reaper", last updated 2021, af.mil/About-Us/Fact-Sheets/Display/Article/104470/mq-9-reaper/

the Reaper being deployed for 24-hours missions if ever required[285], outclassing conventional fighters. For the sake of our comparison, we will consider a target located into a range the MQ-9 can operate within. As our drone leaves the air base and approaches the enemy's border, stealth shall assure its concealment providing protection from radar detection, SAMs and other defensive systems. Stealth applied in the drone domain, nonetheless, is quite a complex topic to develop. When most scholars refer to drones being stealthier than conventional aircraft they affirm so due to drones reduced dimensions, which of course will generate a lower return of radar waves to the receiving antenna of the defenders. But these drones, being so small, will also have a very limited range which would exclude them from reaching distant targets, reducing as well their overall combat and strategic potential. The MQ-9, with its 20 meters wingspan, is smaller than an F-35 but its body-shaping cannot be defined as proper-stealth, since it lacks necessary flat surfaces while presenting huge wings and tail wings which are very probable to raise the drone's overall RCS[286]. The operator could bypass such risk by flying extremely low to the ground, hoping to be excluded by the emitting antenna field. This however implies harder challenges for the remote pilot and greater risk of visual spotting by some ground troops who could kick-off the kill chain at any time. The significantly lower heat levels generated by the engine, at the same time, will grant at least a better degree of concealment from infrared or heat-seeking sensors. Now into the enemy air space, our drone has to look for the target. In order to do so, the Reaper is equipped with a wide range of sensors, working together to maximize the compressive awareness of the vehicle: cameras, infrared sensors and cameras, laser designator and laser illuminator work in combination with each other with considerable synergy[287]. In our imaginary mission, the drone is likely to employ the air-to-ground missile AGM 114-Hellfire due to its laser guidance which allows the drone to strike with remarkable precision[288]. The operator will

[285] *Ibis*.

[286] Alex Hollings, "Can The Military Save This Deadly Terrorist Hunter from the Scrap Heap?", Popular Mechanics, 2021, www.popularmechanics.com/military/a37623821/the-end-of-the-mq-9-reaper/

[287] US Air Force, "MQ-9 Reaper", last updated 2021, af.mil/About-Us/Fact-Sheets/Display/Article/104470/mq-9-reaper/

[288] Military.com, "AGM 114-Hellfire", military.com/equipment/agm-114-hellfire

face almost no delay in the execution of the operation since the connection links required to operate the Reaper, composed of satellites and ground control stations, are highly complex but extremely effective at the same time[289]. Once the target is hit and the defenders reaction forced, drones will meet few chances of survival. Strained to elude radar surveillance, it is probable for our drone to be located, tracked then shot down without particular challenges if the defenders personnel is enough experienced: the low speed of the MQ-9 will not allow for a quick withdrawal and, if some fighters are sent to check the area, it will face absolutely no means of survival if localized. Moreover, its lower speed would allow enemy MANPADs to lock-on without particular troubles. Nonetheless, expendability is one of the main elements that mark the difference with them and other, traditional, military machines: since no friendly human lives are at stake, the outcome of the mission could still be considered successful if the drone has been shot down but the target has been hit and destroyed previously.

6.5 Drones offensive advantage flaws

The limits of drones' offensive advantage have been pretty evident throughout the whole execution of our fictional striking mission. Considering the different elements and characteristics inherent to drones, this comparison has highlighted more their limitations rather than potentialities, going completely against the drone revolution hypothesis. If such a thesis would be more prone to find empirical confirmations, we would have instead described the drone overtaking with extreme ease conventional defensive systems, or at least challenge the defenders by a superior order of difficulty compared to the F-35's. At the state of the art, it is strongly plausible that our MQ-9 would have not even reached its target if it was located under the skies of nations with powerful and skilled militaries such as Russia as well as China, suggesting that the drone revolution may not be that power-

[289] General Atomics, "New Block 50 Ground Stations Flies MQ-9 Reaper", 2019, ga-asi.com/new-block-50-ground-control-station-flies-mq-9-reaper

equilibrium breaker that some researchers suggest it to be. Drones have few, if not minimal, chances of surviving defensive systems or dogfighting if their position is ever to be located and, despite them being more expendable than other military assets, this feature alone cannot entail a complexive superior offensive advantage. Combat-focus drones with clear and specific stealth features are not ready yet for full combat operativity and they will have to implement more effective stealth capabilities in their body-shaping to present real challenges in the execution of the kill chain. Drones' sensors that indue and improve combat awareness must improve exponentially to rival the ones of 5th generation fighters. Internal weapons bay, which lower RCS considerably, will become necessary. However, finding an appropriate equilibrium between stealth, engine, weight, payload capacity and autonomy will not be an easy assignment and the long time for the development of prototypes seems to prove this even furtherly, hinting how drones mass production may be something not so universally-achievable as it could be believed: it is probable to expect drone production to be restricted to nations with already powerful absorptive capabilities, strong industrial assets and advanced know-how in robotics as well as artificial intelligence. The possibility to swarm an enemy defensive system in order to overwhelm it may be far from effective against powerful actors and would probably result in a high-priced failure rather than a prodigious success. Considering the MQ-9 Reaper cost per unit to be around 4 up to 5 million US dollars and so being far from the cheap, affordable prices described by the drone revolution supporters. Moreover, these costs do not cover all the weapons, equipment, ground stations as well as training that must come with every single unit to factually utilize it and the complexive expenditures could reach astonishing numbers in the long run[290]. A lack of speed is another crucial missing characteristic in the drone domain, since rapid movement can increase the difficulty in tracking the intruder while coming in handy in other crucial situations such as shrinking the window of vulnerability while crossing the enemy airspace. Moreover, the effect of cyber-attacks or electronic warfare against these platforms could very

[290] Winslow Wheeler, "2. The MQ-9 Cost and Performance, TIME, 2012, nation.time.com/2012/02/28/2-the-mq-9s-cost-and-performance/

plausibly render a whole fleet of drones unusable if their complex, and maybe vulnerable, remote-control apparatus would be damaged to some degree, underlining how purchasing and maintaining operative drones may actually be an exponentially harder challenge than the drone revolution thesis suggests. Overall, drones' offensive advantage seems to be currently restricted to some specific strategic contexts and environments that permit them to shine the most, rather than an absolute feature destined to reshape international power assets.

6.6 Outcome

The F-35 is clearly the "winner" of the comparison presented by this paper. Winner, in this case, does not mean that 5th generation fighters promote radical shifts in the offense-defense balance, but for sure they possess capabilities that no other military equipment, vehicle or component can provide. The overall balance however is unlikely to be modified by such technology, since the lethality of air domain entails a degree of vulnerability that stealth was only able to partially mitigate. Moreover, the global offense-defense balance takes into consideration so many elements that in our contemporary age it is extremely unlikely, if not impossible, to unravel a technology capable of promoting revolutionary switches against the established equilibrium.

The costs and experience required to operate in 5th generation fighters fleets are possessed only by a restricted number of already powerful global actors, which however, in return, grant to themselves the possibility to carry on missions that would be impossible to perform by other means: our comparison proved this point coherently and drones are not capable of filling such gaps in favor of less powerful actors. The fact that drones do not belong to an extremely oligopolistic industry like fighter jets may not be a correct assumption too, since all the equipment, know-how, materials and experience they demand may be not too distant from fighters' ones in the long run. Moreover, as drones-related examinations progress, an increasingly clearer picture of the drones' industry seems to allude at how their mass scale production may be restricted to some rich nations with an already

strongly established knowledge in technology as well as cyber branches, going against the assumption that drones are easy and cheap to build. Furthermore, drones do not possess the features and capability to assert their dominion over the skies and do not represent almost any kind of threat for new generation fighters, which outclass their unmanned counterparts by an order of magnitude. Overall, the drone revolution hypothesis may have been based on too many preliminary assumptions that are not prone to find empirical confirmation if their features and capabilities are addressed in detail. Nonetheless, drones hold the potential to provide huge changes in how we project, make and ponder war but their technology is simply not advanced enough to promote deep as well as long-lasting alterations. Because of that, drones have an important role in conflict-situations where they can provide support to other compartments of the military thanks to their expendability, rather than directly substitute the employment of manned vehicles considering combat-potential alone. Yet, their expendability makes them important resources for actors with lesser combat power, which can rely on drones and a little bit of improvisational skills in order to close the gap between them and the enemy at least in the early stages of the conflict. In the long run, however, drones are not expected to be the determinant for the final outcome of wars. Where drones truly shine the most are scenarios where their unmanned-pilot features allows for cheaper and more effective results: surveillance and border control missions, for example, may benefit exponentially from drones' employment rather than traditional manned vehicles. Also reconnaissance may be a field that pays-off drones' employment, in particular for infantry units which could exploit the benefits of a wide-spectrum exploration without exposing themselves to enemy fire or giving away their position by breaking radio silence.

Drones will have to wait a considerable amount of time before having the chance of overtaking the apex position of fighter jets in the air dominion, with huge consequences on strategic, economic and legal aspects. That day, however, is still far away. In conclusion, it could be stated that drones

have not overtaken the offensive advantage of 5th generation stealth fighter jets and are not likely to surpass them in the foreseeable future.

7. Conclusion and Final Considerations

7.1 Conclusions and Final Considerations

The result of the confrontation presented by this paper outlined different elements that brought to the fore the asserted supremacy of 5th generation stealth fighters in the race for air power over their unmanned counterpart. Furthermore, drones proved to lack crucial engineering features which would otherwise allow them to challenge fighters on a more leveled field. At the same time, the points proposed by the drones revolution hypothesis have been put in question on different occasions. The overall global balance for both offensive and defensive predisposition does not seem to be vulnerable by the coming of new technologies, neither drones nor stealth fighters, and it is very unlikely for our current balance to be ever drastically altered, considering the deterrence given by nuclear warheads.

Even if, for today's standard, manned vehicles still hold the dominion of the skies, it comes across as logical to believe that unmanned vehicles will be destined to supersede manned ones in the long run, at least in a wider and wider window of employment. In order to achieve such a shift, however, researchers will have to precisely address how this passage to fully autonomous fleets could actually be free from risks or vulnerabilities of some kind, with the cyber dimension being the one with the most potential to break automated machines' power. Such a shift is not going to revolutionize the global distribution of power, since drones' production will be carried on mostly by already powerful countries with strong and long-established military, economic as well as industrial assets. The barriers presented by absorptive capability, know-how, skills and software technology required for drone manufacturing are not easy to overcome and, because of that, only few countries will be able to produce, run and maintain operative drones fleets in the future. So, it would not be wrong to expect the countries that today operate and build 5th generation fighters to be the same which one day will hold the most advanced and large fleets of unmanned UAVs and UCAVs. With new information starting to leak out about the Next Generation Air Dominance (NGAD) program carried on by the

United States Air Force, we may expect to find further confirmation of our results. The air dominance program hints at the possibility that fighter jets and drones will eventually work together on the same platforms one day in the future. The program, indeed, seems to point at the development of new 6th generation fighters that will eventually implement drones into their mission equipment. Acting as wingmen, unmanned aircrafts could escort the aircraft and provide different capabilities for reconnaissance, battle awareness, protection and target striking[291]. Exponential improvements on the fighter itself will consist, according to unofficial sources, of new stealth technologies which put heavy emphasis on hard body-shaping, maybe improved by devices capable of directly denying radar waves' return[292]. Nonetheless, the absolute secrecy carried on by the US government and the firms involved in the project, such as Lock-Heed Martin as well as Northrop Grumman, suggests that this program will be crucial for future air dominance targets. Costs will also play a relevant role for the program's future, as the Joint Strike Fighter program previously taught, but it is unclear how many F-22 Raptors models will be replaced by NGAD[293].

In conclusion, the future for air warfare appears to be strictly linked to drones' technology but the complete overtake of unmanned aircraft over manned ones seems not destined to happen anywhere soon. Instead, a more realistic combination of drones and stealth fighters seems to be the most plausible and efficient way to pursue air dominance in the upcoming future.

[291] Sakshi Tiwar, "America's 'Black Program' - NGAD Loyal Wingman Drone Concept Inches Closer to Reality, Competition in 2024", The Eurasian Times, 2022, eurasiantimes.com/ngad-loyal-wingman-drone-concept-inches-closer-to-reality/

[292] Valius Venckūnas, "NGAD in pictures: What might the US sixth-generation fighter jet look like?", Aero Time, 2022, aerotime.aero/articles/31756-what-do-we-know-about-ngad-heres-every-concept-so-far

[293] Valerie Insinna, "The Air Force's secret next-gen fighter has reached development phase", Breaking Defense, 2022, breakingdefense.com/2022/06/the-air-forces-secret-next-gen-fighter-has-reached-development-phase/

8.0 Italian Summary

8.1 Italian Summary

Questo elaborato nasce con l'obiettivo di presentare un'esaustiva ricerca sulla tecnologia relativa ai droni, per decretare se abbia o meno le potenzialità per mitigare il vantaggio offensivo garantito dai caccia stealth di quinta generazione. Allo stesso tempo, la ricerca punta a scandagliare l'effettiva veridicità della "drone revolution" negli affari militari.

Senza dubbio, i droni rappresentano un'allettante alternativa per una amplissima finestra di impieghi diversi, a partire ovviamente dalla conquista della superiorità aerea. Inoltre, i loro costi contenuti, sia in termini di risorse[294] sia di vite umane, rendono i droni una tecnologia di crescente interesse per nazioni ed alleanze militari.

I cieli sono sempre stati uno degli ambienti più ostili in cui combattere e alcune delle caratteristiche intrinseche dei droni potrebbero erodere la generale superiorità detenuta attualmente dai costosissimi caccia stealth di quinta generazione. Comprendere il ruolo dei droni nella corsa alla supremazia aerea sarà di fondamentale importanza: in quanto tecnologia innovativa, le potenzialità per il loro utilizzo per ruoli sia strategici che di combattimento sono ancora da comprendere a fondo.

Per confrontare e valutare il vantaggio offensivo offerto dalle due tecnologie analizzate, viene innanzitutto presentata una dettagliata analisi sulla tecnologia stealth, che ha cambiato irrimediabilmente la guerra aerea contemporanea. Le capacità stealth, infatti, sono ormai un prerequisito imprescindibile per i conflitti aerei contemporanei e futuri.

Successivamente, l'elaborato introduce le diverse contromisure sviluppate nel corso del tempo per fronteggiare al meglio i veicoli stealth. Le tecnologie descritte sono potenzialmente in grado non solo

[294] Costi ridotti se comparati ai caccia stealth di quinta generazione. Infatti, come l'elaborato presenta dettagliatamente, i requisiti richiesti per operare e mantenere operative flotte di droni rappresentano enormi entry-barriers che la maggior parte degli stati non sarà mai in grado di superare con successo.

di abbattere tali veicoli ma anche di negare, anche solo parzialmente, l'occultamento ai radar garantito dallo stealth, una caratteristica cruciale che garantisce ai veicoli potenzialità straordinarie in ambito strategico e tattico.

In seguito, l'elaborato si concentrerà su descrizione e presentazione sia dei caccia stealth di quinta generazione che dei droni, con una panoramica sul loro ipotizzato ruolo rivoluzionario in ambito militare. Questi capitoli aiuteranno nella valutazione non solo delle loro caratteristiche e delle loro virtù tecnologiche, ma esploreranno a fondo anche la loro dimensione economica ed industriale. Tali elementi, infatti, pur non essendo strettamente legati al combattimento o all'impiego strategico, sono fondamentali per comprendere appieno le sfide che droni e caccia stealth presentano alle nazioni intenzionate a implementare le rispettive tecnologie nelle proprie forze armate.

Infine, verrà proposta un'analisi comparativa tra le due parti. La variabile fondamentale per stabilire il vantaggio offensivo sarà rappresentata dalle possibilità a disposizione dei difensori di localizzare ed ingaggiare l'intruso, prima che quest'ultimo possa distruggere un punto strategico localizzato nel cuore del loro territorio. L'efficacia dello stealth, tecnologia che rigetta la struttura "all-or-nothing", è soggetta a innumerevoli variabili che possono comportare un migliore, o peggiore, occultamento dai sensori nemici. Questa comparazione dovrebbe rendere possibile riconoscere quale tecnologia possieda i mezzi e le possibilità migliori per condurre e concludere la missione con successo. La libertà di movimento di cui solo i veicoli stealth possono godere una volta entrati in un territorio nemico è un parametro coerente per quantificare il vantaggio offensivo complessivo, e se una delle due parti abbia superato l'altra in tali termini. Oltre a ciò, ulteriori parametri verranno presi in considerazione. La tecnologia che garantirà maggiori chances di occultamento radar, area operativa raggiungibile, possibilità di sopravvivere ad uno scontro sarà ritenuta preferibile. Il caccia F-35 verrà preso come esponente delle capacità dei caccia stealth di quinta generazione, vista l'enorme quantità di fonti disponibili che riflettono anche il suo ruolo cruciale nelle forze aeree occidentali. Il drone

MQ-9 Reaper, invece, essendo considerato dalla maggior parte degli esperti l'UCAV più letale ed avanzato in pieno stato di servizio, aiuterà invece a rappresentare le capacità dei droni contemporanei.

Bibliography

Michale E. Brown, Owen R. Coté Jr, Sean M. Lynn-Jones and Steve E. Miller, "Offense, Defense, and War" MIT Press, 2004

George H. Quester, "Offense and Defense in the International System", John Wiley & Sons, 1977

Jack S. Levy, "The Offensive/Defensive Balance of Military Technology: A Theoretical and Historical Analysis", International Studies Quarterly, 1984

Andreas Lorenz, Messengers of Death: Are Drones Creating a New Global Arms Race?", Der Spiegel, 2011

Christopher Coker, "Warrior Geeks: How 21st Century Technology is Changing the Way We Fight and Think about War", London: Hurst, 2013

Antonio Calcara, Andrea Gilli, Mauro GIlli, Raffaele Marchetti, Ivan Zaccagnini, "The Drone Revolution in Military Affairs? Understanding the Hider-Finder Competition in Air Warfare", International Security Volume 46, Issue 4, MIT Press, 2022

Michael J. Boyle, "The Drone Age: How Drone Technology Will Change War and Peace", Oxford: Oxford University Press, 2020

Michael Mayer, "The New Killer Drones: Understanding The Strategic Implications of Next-Generation Unmanned Combat Aerial Vehicles", International Affairs, Vol. 91, 2015

Heiko Borchet, Torben Schutz, Joseph Verbovsky, "Beware the Hype. What Military Conflicts in Ukraine, Syria, Libya and Nagorno-Karabakh (Don't) Tell Us About The Future Warfare", ResearchGate, 2021

Franz-Stefan Gady, " Useful, but Not Decisive: UAVs in Libya's Civil War" International Institute for Strategic Studies, 2019

Dan Gettinger, "Drones Operating in Syria and Iraq", Annandale-on-Hudson, N.Y.: Center for The Study of the Drone, 2016

Christopher Phillis, "The Battle for Syria: International Rivalry in the New Middle East", Conn.: Yale University Press, 2016

School of Advanced Airpower Studies, "The Evolution of Airpower Theory", Air University Press, 1997

Air University, "Doctrine Advisory: Control of the Air", 2017

Jeffrey W. Hamstra, "The F-35 Lighting II: From Concept to Cockpit", Amer Institute of Aeronautics, 2019

Keir A. Lieber, "Grasping The Technological Peace", Harvard College and Massachusetts Institute of Technology, International Security Vol.25, 2000

Rebecca Slayton, “What Is the Cyber Offense-Defense Balance?”, International Security Vol.41, MIT Press, 2016

Robert Jervis, “Cooperation Under The Security Dilemma”, World Politics Vol.30, Princeton University Press, 1978

George H. Quester, “Offense and Defense In the International System”, Routledge, 2002

Karen R. Adams, “Attack and Conquer”, Harvard College and Massachusetts Institute of Technology, International Security Vol.28, 2003

Drew Herrick, Trey Herr, “Combating Complexity: Offensive Cyber Capabilities and Integrated WarFighting”, George Washington University and Harvard University, 2016

Van Evera, “The Cult of Offensive and the Origins of the First World War”, International Security Vol.9, MIT Press, 1984

Joachim Remark, “The Origins of World War I, 1872-1914”, Hinsdale, III: Dryden Press, 1967

Barbara Tuchman, “The Guns of August”, New York: Random House, 1938

Glenn H. Snyder, “Deterrence and Defense”, Princeton University Press, 1961

G. A. Rao and S. P. Mahulikar, “Integrated review of stealth technology and its role in airpower”, The Aeronautical Journal, volume 106, Cambridge University Press, 2002

Ben R. Rich and Leo Janos, “Skunk Works”, Little, Brown and Company, 1994

Gene Poteat, “Stealth, Countermeasures, and ELINT, 1960-1975”, Studies in Intelligence 48, US Central Intelligence Agency, 2013

Rebecca Grant, “The Radar Game”, Mitchell Institute, 2010

John Shaeffer, “Understanding Stealth”, Marietta Scientific, 2018

Steven Biddle and Ivan Oelrich, “Future Warfare in the Western Pacific”, International Security Vol.41, MIT Press, 2016

Maj. Gen. Mark Barrett and Col. Mace Carpenter, “Survivability in the Digital Age: The Imperative For Stealth”, Mitchell Institute, 2017

Col. Neil G. Kacena, “Stealth: An Example of Technology’s Role in the American Way of War”, Air War College, Air University, 1995

Lee B. Kennet, “The First Air War, 1914-1918”, New York: The Free Press, 1991

Alan Stephens, “The War in the Air 1914-1994”, Air University Press, 2001

William Mitchell, “Memoirs of World War I”, New York: Random House, 1960, the memoir was first published in 1928

David Pritchard, “The Radar War: Germany’s Pioneering Achievement, 1904-45”, Harper Collins, 1989

Matthew Cooper, “The German Air Force, 1933-1945: anatomy of a Failure”, New York: Jane’s, 1981

John B. McPeterson (Editor), “The Army Air Forces’ ‘Confidential’ Picture History of World War II”, 7th book out of 8, James Patron & Co., 1980

Robert Frank Futrell, “Ideas, Concepts and Doctrine: Basic Thinking in the US Air Force, 1907-1960”, Air University Press, 1989

Maj. A. J. C. Lavalle, “The Tale of Two Bridges and the Battle for the Skies Over North Vietnam”, USAF Southeast Asia Monograph Series, Washington DC: Office of Air Force History, 1976

Peter W. Merlin, “Design and Development of the Blackbird: Challenges and Lessons Learned”, American Institute of Aeronautics and Astronautics, 2009

Jeffrey T. Richelson, “Science, Technology and the CIA”, The National Security Archive, The George Washington University Press, 2013

M.W. Browne, “Two rivals designers led the way to stealthy warplanes”, The New York Times, 1991

David Baker, “Fifth Generation Fighters”, Mortons Media Group, 2021

Barrett Tillman and Dan Pedersen, “Top Gun: An American Story”, Hachette Books, 2019

Bill Sweetman, “Ultimate Fighter: Lock-Heed Martin F-35 Joint Strike Fighter”, Zenith press, 2004

Terje Johnsen and Karl Erik Olsen, “Bi- and Multistatic Radar”, RTO NATO, 2006

Marvin B. Schaffer, “Concerns about Terrorists with manportable SAMS”, Rand, 1993

Mark A. Lorell and Hugh P. Laveaux, “The Cutting Edge”, Rand, 1998

Frederic P. Miller, Agnes F. Vandome and John McBrewster, “Fourth generation Jet Fighter”, Alphascript Publishing, 2011

Mike Wallance and Bill Holder, “LockHeed-Martin F-22 Raptor”, Schiffer Military, 1998

Peter Aleshire, “The Eye Of The Viper: The Making of an F-16 Pilot”, Lyons Pr, 2005

Jeffrey W. Hamstra, “The F-35 Lighting II: from Concept to Cockpit”, Amer Institute of Aeronautics, 2019

Andrea Gilli and Mauro Gilli, “Why China has not Caught Up Yet”, International Security Vol.43, MIT Press, 2018

Reg Austin, “Unmanned Aircraft Systems: UAVS Design, Development and Deployment”, Wiley, 2010

Government Accounting Office, “Agencies Could Improve Information Sharing and End-Use Monitoring on Unmanned Aerial Vehicles Exports” (Washington DC: GAO, 2012)

Christopher Coker, “Warrior Geeks: How 21st Century Technology is Changing the Way we Fight and Think About War”, Hurst Publisher, 2013

Peter L. Bergen and Daniel Rothenberg, “Drone Wars: Transforming Conflict, Law and Policy”, Cambridge University Press, 2014

P.W. Singer, “Wired of War: The Robotics Revolution and Conflict in the 21st Century”, Penguin Press, 2009

Bart Custers, “The Future of Drone Usage: Opportunities and Threats from Ethical and Legal Perspective”, Information technology and Law Series, Asser Press, 1996

Michael Knights, “Cradle of Conflict: Iraq and the birth of Modern U.S. Military Power”, Naval Institute Press, 2005

Andrea Gilli and Mauro Gilli, “The Diffusion of Drone Warfare? Industrial, Organizational and Infrastructural Constraints: Military Innovations and the Ecosystem Challenge”, Security Studies Volume 25, 2016

Dwight E. Phillips Jr., “Reengineering Institutional Culture and American Way of War in the Post-Vietnam U.S. Army, 1968-1989”, University of Chicago, 2014

Antonio Calcara, Andrea Gilli, Mauro Gilli, Raffaele Marchetti and Ivan Zaccagni, “The Drone Revolution in Military Affairs? Understanding the Hider-Finder Competition in Air Warfare”, International Security Volume 46, Issue 4, MIT Press, 2022

Heilenday Frank, “Principles of Air Defense and Air Vehicle Penetration”, Defense Technical Information Center, 2000

Dan Gettinger, “Drones Operating in Syria and Iraq”, Center for the Study of the Drone, Bard College, 2016

Jason Pack and Wolfgang Pusztai, “Turning the Tide: How Turkey Won the War in Tripoli”, Middle East Institute, 2020

Ralph Schield, “Russian AirPower’s Success in Syria: Assessing Evolution in Kinetic Counterinsurgencies”, Journal of Slavic and Military Studies, Vol.31, No.2, 2018

Timothy Thomas, “Russian Lessons Learned in Syria: An Assessment”, MITRE, 2020

Peter Paret, Gordon A. Craig and Felic Gilbert, “Makers of Modern Strategy: From Machiavelli to Nuclear Age”, Princeton University Press, 1986

Michael I. Handel, “Masters of War”, Routledge, 2001

Fabrizio Coticchia, “A Controversial Warplane: Narratives, Counternarratives and the Italian Debate on the F-35”, Alternatives: Global, Local, Political, Vol. 41, Sage Publications, 2016

Alessandro Marrone, “Italy and the F-35: Rationales and Costs”, International Journal, Vol. 68, 2013

Stephen Biddle, “Victory Misunderstood: What the Gulf War Tells Us about the Future of Conflicts”, International Security, Vol. 21, MIT Press, 1996

Giulio Douhet, “Il Dominio dell’Aria”, Historical Office of Italian Military Aeronautic, 2022 (First Edition 1921)

Patrick B. Johnson and Anoop K. Sarbahi, “The Impact of US Drone Strikes on Terrorism in Pakistan”, International Studies Quartely, Vol. 60, 2016

Webography

Nailia Bagirova, “After Ukraine, ‘whole world’ is a customer for Turkish drone, maker says”, Reuters, 2022, reuters.com/business/aerospace-defense/exclusive-after-ukraine-whole-world-is-customer-turkish-drone-maker-says-2022-05-30/

Kimberly Johnson, Meg Godlewski, “Turkish Bayraktar Drone Inspires Son of Ukrainian Resistance”, Flyingmag.com, 2022, flyingmag.com/turkish-bayraktar-drone-inspires-song-of-ukrainian-resistance/

H.I. Sutton, “Incredible Success of Ukraine’s Bayraktar TB2: The Ghost Of Snake Island”, NavalNews, 2022, navalnews.com/naval-news/2022/05/surprising-success-of-ukraines-bayraktar-tb2-the-ghost-of-snake-island/

Twitter.com/DefenseU

Stephen Witt, “The Turkish Drone That Changed The Nature of Warfare”, TheNewYorker, 2022, newyorker.com/magazine/2022/05/16/the-turkish-drone-that-changed-the-nature-of-warfare

Ragip Solyu, “Ukraine Received 50 Turkish Bayraktar TB2s Drones Since Russian Invasion”, Middle East Eye, 2022, middleeasteye.net/news/russia-ukraine-war-tb2-bayraktar-drones-fifty-received

David Hambling, “New Turkish Bayraktar Drones Still Seem To Be Reaching Ukraine”, Forbes, 2022, forbes.com/sites/davidhambling/2022/05/10/new-turkish-bayraktar-drones-still-seem-to-be-reaching-ukraine/?sh=4eb4528e685b

Philips Payson O’Brien, Edward Stringer, “The Overlooked Reason Russia’s Invasion is Floundering”, The Atlantic, 2022, theatlantic.com/ideas/archive/2022/05/russian-military-air-force-failure-ukraine/629803/

Harry Boneham, “Russia’s Struggle to Establish Air Superiority in Ukraine”, GlobalData, Army Technology, 2022, army-technology.com/comment/air-superiority-in-ukraine/

Facebook.com/president.gov.ua/videos/417501393181766/

Christopher Woody, “Top USA Air Force General Says the Russian Air Force’s Struggles in Ukraine are Surprising Because Russia is Fighting its ‘Own Systems’”, Business Insider, 2022, businessinsider.in/international/news/the-russian-air-forces-struggles-in-ukraine-are-surprising-because-theyre-fighting-their-own-systems-top-us-air-force-general-says/articleshow/92398335.cms

David Axe, “Russian Jets Are Flying So Low To Dodge Ukrainian Air-Defense That They’re Running Into The Ground”, Forbes, 2022, forbes.com/sites/davidaxe/2022/06/24/russian-jets-are-flying-so-low-to-dodge-ukrainian-air-defenses-that-theyre-running-into-the-ground/?sh=22b72021a251

Maximilian K. Brember, Kelly A. Grieco, “In Denial About Denial: Why Ukraine’s Air Success Should Worry the West”, WarOnTheRocks, 2022, warontherocks.com/2022/06/in-denial-about-denial-why-ukraines-air-success-should-worry-the-west/

Brent M. Eastwood, “Russia’s much-touted Su-57 stealth fighter jet doesn’t appear to be showing up in Ukraine”, Business Insider, 2022, businessinsider.com/su57-why-russia-wont-send-new-stealth-fighter-to-ukraine-2022-6?r=US&IR=T

TASS, “Russia’s Su-57 Outshines US Fifth-Generation Fighters, Says Expert”, Russian News Agency, 2021, tass.com/defense/1352447

Kris Osborn, “Russian Su-57 Fighter Jets Overmatched Against US and NATO F-35 Firepower”, Warrior Maven, Center for Military Modernization, 2022, warriormaven.com/russia-ukraine/russian-su-57-f-35-nato

Wesley Culp, “Russia Only Has 10 Su-57 ‘Felon’ Stealth Fighters”, 19fortyfive.com/2022/06/russia-only-has-10-su-57-felon-stealth-fighters, 2022

Thomas Newdick, “Let’s Talk About The Rumors That Russia’s Su-57 Is Participating In The War In Ukraine”, The WarZone.com/lets-talk-about-the-rumors-that-russias-su-57-is-participating-in-the-war-in-ukraine

Tim Hsia and Jared Sperli, “How Cyber Warfare and Drones Have Revolutionized Warfare”, At War blog, New York Times, 2013, nytimes.com/atwar.blogs.nytimes.com/2013/06/17/how-cyberwarfare-and-drones-have-revolutionized-warfare/

“Select Enemy. Delete”, The Economist, March 1997, economist.com/special/1997/03/06/select-enemy-delete

Elliott Negin, Lisbeth Gronlund, “How Much Does it Cost to Create a Single Nuclear Weapon?”, TheEquation.com, 2013, ucsusa.org/elliott-negin/how-much-cost-to-create-nuclear-weapon/

John T. Corell, “History of Stealth: From Out of the Shadows”, Air Force Magazine, 2019, airforcemag.com/article/history-of-stealth-from-out-of-the-shadows/

Gp. Cap. Joseph Noronha, “Countering Stealth Aircraft Technology: The Race to See Through ‘Invisibility’”, Indian Defense Review, 2018, indiandefencereview.com/news/countering-stealth-aircraft-technology-the-race-to-see-through-invisibility/

John A. Tirpak, “With Stealth in the Balkans”, Air Force Magazine, 1999, airforcemag.com/article/1099stealth/

Dario Leone, “The Story of the F-117 Nighthawk Airstrikes Over Baghdad That Marked The Beginning of Operation Iraqi Freedom”, The Aviation Geek Club, 2017, theaviationgeekclub.com/story-f-117-nighthawk-airstrikes-baghdad-marked-beginning-operation-iraqi-freedom/

Valerie Insinna, “How Many F-35 does the Air Force need?”, Defense News, 2021, defensenews.com/digital-show-dailies/air-force-association/2021/09/07/new-us-air-force-study-asks-whats-the-right-number-of-f-35s/; Rebecca Grant, “The Radar Game”, Mitchell Institute, 2010

Governmentattic.org, “Beacon Hill Report: Problems of Air Force Intelligence and Reconnaissance, Project Lincoln, Massachusetts Institute of Technology (MIT)”, 1952, governmentattic.org/12docs/USAF-BeaconHillReport_1952.pdf

Maj. A. J. C. Lavalle, “The Tale of Two Bridges and the Battle for the Skies Over North Vietnam”, USAF Southeast Asia Monograph Series, Washington DC: Office of Air Force History, 1976; Mark Carlson, “Operation Spring High: Thuds vs. SAMs”, Historynet, 2019, historynet.com/operation-spring-high-thuds-vs-sams/

Ray Alderman, “Radar cross section: The measure of stealth”, Military Embedded Systems, 2017, militaryembedded.com/radar-ew/signal-processing/radar-cross-section-the-measure-of-stealth

Logan Nyle, “How the legendary B-2’s stealth actually works”, We Are The Mighty, 2022, wearethemighty.com/mighty-tactical/how-b2-stealth-bomber-works/

Eli Fuhrman, “An F-22 Stealth Fighter Flew Under an Iranian F-4 Phantom (Undetected)”, The National Interest, 2021, nationalinterest.org/blog/buzz/f-22-stealth-fighter-flew-under-iranian-f-4-phantom-undetected-190472

Alex Hollings, “How an F-22 Pilot Scared Iranian Fighters Away With Just One Sentence”, SandBoxx, 2021, sandboxx.us/blog/how-an-f-22-pilot-scared-iranian-fighters-away-with-just-one-sentence/

Robbin Laird, “The Role of Fighters in Contested Airspace: The International Fighter Conference Debates the Issue”, Defense.info, 2018, defense.info/air-power-dynamics/2018/11/the-role-of-fighters-in-contested-airspace-the-international-fighter-conference-debates-the-issues/

EurAsian Times Desk, “Who is Winning the Race between US, Russia & China to Develop World’s First Sixth-Gen Fighter Jet?”, The EurAsian Times, 2020, eurasiantimes.com/who-is-winning-the-race-between-us-russia-china-to-develop-worlds-first-sixth-gen-fighter-jet/

John A. Tirpak, “The sixth Generation Fighter”, Air Force Magazine, 2009, airforcemag.com/article/1009fighter/

Apoorva Jain, “Dogfighting, Stealth Jets Could Become Osbolete as US, China Looks to Arm Their Fighter Jets with ‘New Age Weapons’”, The AurAsian Times, 2021, eurasiantimes.com/dogfighting-stealth-jets-could-become-obsolete-as-us-china-look-to-arm-their-fighter-jets-with-new-age-weapons/; Alex Hooling, “Are the days of dogfighting over? An in-depth air combat analysis”, Sanboxx, 2022, sandboxx.us/blog/are-the-days-of-dogfights-over-an-in-depth-air-combat-analysis/

Dario Leone, “An In-Depth Analysis of How Serbs Were Able to Shoot Down an F-117 Stealth Fighter During Operation Allied Force”, The Aviation Geek Club, 2020, theaviationgeekclub.com/an-in-depth-analysis-of-how-serbs-were-able-to-shoot-down-an-f-117-stealth-fighter-during-operation-allied-force/

Danelle Au, “Snapping Links in the Kill Chain: Lessons Learned by a Stealth Pilot”, Security Week, 2017, securityweek.com/snapping-links-kill-chain-lessons-learned-stealth-pilot

Britannica, “Surface-to-air-missiles”, britannica.com/technology/surface-to-air-missile

Alex Hollings, “The US’ Best Stealth Jets are Pretty Easy to Spot on Radar, but that Doesn’t Make It Any Easier to Stop Them”, Business Insider, 2022, businessinsider.com/radars-can-see-best-stealth-jets-but-cant-stop-them-2022-7?r=US&IR=T

BrahMos Aerospace, “Classification of Missile”, brahmos.com/content.php?id=10&sid=9; Britannica, “Surface-to-air-missiles”, britannica.com/technology/surface-to-air-missile

Thomas Withington, “Identification Friend or Foe “, European Security & Defense, 2022, euro-sd.com/2022/01/articles/exclusive/24434/identification-friend-or-foe/

Alex Hollings, “The S-400 myth: Why Russia’s Air Defense Prowess is Exaggerated”, Sandboxx, 2022, sandboxx.us/blog/the-s-400-myth-why-russias-air-defense-prowess-is-exaggerated/

Tyler Rogoway, “Ukraine Might Get IRIS-T SLM Surface-to-Air Missile System: Reports”, The Drive, The Warzone, 2022, thedrive.com/the-war-zone/ukraine-might-get-german-iris-t-slm-medium-range-sam-system-reports; Air Force Technology, “Medium-Range Surface-to-Air Missile (MRSAM)”, www.airforce-technology.com/projects/medium-range-surface-to-air-missile-mrsam/

Yuferev Sergey, “Fim-43 Red Eye”, 2018, topwar.ru/147209-ruchnye-kompleksy-pvo-chast-2-pzrk-fim-43-redeye.html

Military Factory, “Type 91 (Hand Arrow)”, 2018, militaryfactory.com/smallarms/detail.php?smallarms_id=1181

Army Technology, “The top man-portable air-defense systems (MANPADS)”, 2019, army-technology.com/analysis/man-portable-air-defence-systems/

Thales Group, “STARStreak”, thalesgroup.com/en/markets/defence-and-security/air-forces/advance-air-defence/starstreak; Army Recognition, “Starstreak Missile Manpad”, 2022, armyrecognition.com/british_united_kingdom_missile_systems_vehicles_uk/starstreak_hvm_high_velocity_short-range_surface-to-air_missile_manpads_technical_data_sheet_picture.html

Adam J. Hebert, “Fighters Generations”, Air Force Magazine, 2008, airforcemag.com/article/0908issbf/; David Kindy, “The Day Germany’s First Jet Fighter Set Soar”, Smithsonian Magazine, 2021, smithsonianmag.com/smithsonian-institution/day-germanys-first-jet-fighter-soared-history-180978152/

Shreya Mundhar, “AsF-35 Remains Elusive, Will Indian, UAE Air Forces Be The First Operators of Russia’s New Stealth Fighter Jet?”, The EurAsian Times, 2021, eurasiantimes.com/f-35-elusive-indian-uae-first-operators-of-russia-new-stealth-fighters/

David Axe, “Who’s Going to Pay for Russia’s Checkmate Stealth Fighter? Probably Not Russia”, Forbes, 2021, forbes.com/sites/davidaxe/2021/07/22/whos-going-to-pay-for-russias-checkmate-stealth-fighter-probably-not-russia/?sh=fadc03c21ff5

Kelsey Atherton, “CMMC: Stopping Cyber Espionage Like Chinese Theft of F-35 Data”, BreakingDefense.com, 2021, breakingdefense.com/2021/02/cmmc-stopping-cyber-espionage-like-chinese-theft-of-f-35-data/

Valius Venckunas, “Fact check: How many Sukhoi Su-57 Fighter Jets does Russia have?”, Aerotime Hub, 2022, aerotime.aero/articles/31982-fact-check-how-many-su-57s-does-russia-have

Brian Kim, “South Korea unveils prototype of homegrown KF-X fighter jet”, Defense News, 2021, defensenews.com/industry/techwatch/2021/04/09/south-korea-unveils-prototype-of-homegrown-kf-x-fighter-jet/

Air Force Technology, “Mitsubishi X-2 Shinshin (ATD-X) Advanced Technology Demonstrator”, 2016, airforce-technology.com/projects/mitsubishi-x-2-shinshin-atd-x-advanced-technology-demonstrator/

Burak Ege Bekdil, “Turkey officially launches competition for TF-X fighter engine “, Defense News, 2022, defensenews.com/miltech/2022/07/11/turkey-officially-launches-competition-for-tf-x-fighter-engine/

Roger Mola, “Super Helmet”, Smithsonian Magazine, 2017, smithsonianmag.com/air-space-magazine/super-helmet-180964342/

David Roza, “An F-35 helmet costs more than a ferrari and takes two days to get fitted”, Task & Purpose, 2021, taskandpurpose.com/tech-tactics/air-force-f-35-helmet-fitting

Ashish Dangwal, “World’s 1st Fifth-Gen Fighter Completes 25 Years! Lockheed, Boeing, USAF Celebrate F-22 Raptor’s Global Dominance”, The EurAsian Times, 2022, eurasiantimes.com/worlds-1st-fifth-gen-fighter-completes-25-years-lockheed-boeing/

William Cobb, “The Sukhoi Su-27 Flanker, the Masterpiece of Soviet Design that found itself on Opposite Sides of the Russia-Ukraine War”, The Aviation Geek Club, 2022, theaviationgeekclub.com/the-sukhoi-su-27-flanker-the-masterpiece-of-soviet-design-that-found-itself-on-opposite-sides-of-the-russian-ukraine-war/

Congress.Gov, House Amendment 295-105th Congress (1997-1998), Page 100, after line 15, SEC.8103, congress.gov/amendment/105th-congress/house-amendment/295?r=5&s=7

Fabio Tognolo, “Initial Operational Capability per gli F-35 Lighting II Italiani”, Aviaspotter.it, aviaspotter.it/initial-operational-capability-per-gli-f-35-lightning-ii-italiani/?lang=en

Lock-Heed Martin, “F-35 Brochure”, lockheedmartin.com/content/dam/lockheed-martin/aero/f35/documents/F35_Brochure_5_2022.pdf

Thomas Newdick and Tyler Rogoway, “The F-35C ‘s radar-absorbent skin is looking pretty rough after months at sea”, TheDrive.com, thedrive.com/the-war-zone/44067/the-f-35cs-radar-absorbent-skin-is-looking-pretty-rough-after-months-at-sea

Alex Hollings, “How the F-35 flies the line between failure and success”, Sanboxx, 2021, sandboxx.us/blog/how-the-f-35-flies-the-line-between-failure-and-success/

Valerie Insinna, “F-35 to get more expensive in next deal, program exec says”; Breaking Defense, 2022, /breakingdefense.com/2022/03/f-35-to-get-more-expensive-in-next-deal-program-exec-says/

Lock-Heed Martin, f35.com/f35/global-enterprise/united-states.html

Dmitry Sudakov, “The Checkmate: Unique peculiarities of Russia’s new fighter aircraft”, Pravda.ru, english.pravda.ru/news/science/71220-checkmate/

Dan Parsons, “Worldwide, Drones are in High Demand”, National Defense Magazine, 2013, nationaldefensemagazine.org/articles/2013/5/1/2013may-worldwide-drones-are-in-high-demand

Christopher Coker, “Warrior Geeks: How 21st Century Technology is Changing the Way we Fight and Think About War”, Hurst Publisher, 2013

Kashyap Vyas, “A Brief History of Drones: The Remote Controlled Unmanned Aerial Vehicles (UAVs)”, Interesting Engineering, 2020, interestingengineering.com/innovation/a-brief-history-of-drones-the-remote-controlled-unmanned-aerial-vehicles-uavs

Brennan Devereaux, “Loitering Munitions in Ukraine and Beyond”, War On The Rocks, 2022, warontherocks.com/2022/04/loitering-munitions-in-ukraine-and-beyond/

Imperial Drone Museum, “A Brief History of Drones”, iwm.org.uk, iwm.org.uk/history/a-brief-history-of-drones

Brian Everstine, “Air Force: Lost Predator was shot down in Syria”, AirForceTimes, 2015, airforcetimes.com/news/pentagon-congress/2015/06/29/air-force-lost-predator-was-shot-down-in-syria/

U.S. Air Force, “Reaper moniker given to MQ-9 unmanned aerial vehicle”, af.mil, //www.af.mil/news/story.asp?storyID=123027012

Cap. Anthony L. Bucci, “ The Year in Review: Looking back on 2010 at Hancock Field Air National Ground Base”, 174attackwing.ang.af.mil, 2010, 174attackwing.ang.af.mil/News/Article-Display/Article/439406/the-year-in-review-looking-back-on-2010-at-hancock-field-air-national-guard-base/

Stefano D’Urso, “Al-Qaeda Leader Ayman al-Zawahiri Killed in US Drone Strike. Here’s Everything We Know.”, The Aviationist, 2022, theaviationist.com/2022/08/02/al-qaeda-leader-ayman-al-zawahiri-killed-in-us-drone-strike-heres-everything-we-know/

Shane Harris, Dan Lamothe, Karen DeYoung, Souad Mekhennet and Pamela Constable, “U.S. kills al-Qaeda leader Ayman al-Zawahiri in drone strike in Kabul”, The Washington Post, 2022, washingtonpost.com/national-security/2022/08/01/zawahiri-al-qaeda-killed/

Aaron David Miller, “What the Al-Qaeda Drone Strike reveals About U.S. Strategy in Afghanistan”, Carnegie Endowment for International Peace, 2022, carnegieendowment.org/2022/08/02/what-al-qaeda-drone-strike-reveals-about-u.s.-strategy-in-afghanistan-pub-87616

David A. Fulghum and Bill Sweetman, “New Predator C Hints at Stealth, Weaponry”, Aviation Week, 2009, aviationweek.com/aw/generic/story_channel.jsp?channel=defense&id=news%2FAVENGE041509.xml

General Atomics Aeronautical Systems, “GA-ASI Successfully Executes First Flight of Predator C Avenger”, 2009, www.ga-asi.com/news_events/index.php?read=1&id=186

David Axe, “New Armed Stealth Drone Heads to Afghanistan (and Maybe Iran, too)”, Wired, 2011, wired.com/2011/12/stealth-drone-afghanistan/

Frank J. Bartos, “Shrinking Hardwares, Increasing Functions”, Control Engineering, 2004, controleng.com/articles/shrinking-hardware-increasing-functions/

Military Leak, “Australia to Deliver 300 DefendTex D40 Kamikaze Drones to Ukraine”, MilitaryLeak.com, militaryleak.com/2022/08/26/australia-to-deliver-300-defendtex-d40-kamikaze-drones-to-ukrainia/

Sean Kimmons, “OPAT reducing trainee attrition, avoiding millions in wasted training dollars, officials says”, U.S. Army, 2018, army.mil/article/207956/opat_reducing_trainee_attrition_avoiding_millions_in_wasted_training_dollars_officials_say

Niall McArthy, “The Cost of Training Air Force Fighters Pilots”, Forbes, 2019, forbes.com/sites/niallmccarthy/2019/04/09/the-cost-of-training-u-s-air-force-fighter-pilots-infographic/?sh=4768db9f7973

Tanmay Kadam, “Used by Elite Indian Commando, Ukraine to receive 850 Black Hornet Micro Drones to Penetrate Russian Defenses”, The EurAsian Times, 2022, eurasiantimes.com/commandos-ukraine-to-receive-850-black-hornet-micro-drones/

Franz-Stefan Gady, “Useful, but not decisive: UAVs in Libya’s Civil War”, The International institute for Strategic Studies, 2019, iiss.org/blogs/analysis/2019/11/mide-uavs-in-libyas-civil-war

Tom Cooper, “Drones are Dropping Like Flies from the Sky Over Syria. Shoot down are becoming commonplace”, War is Boring, 2017, warisboring.com/drones-are-dropping-like-flies-from-the-sky-over-syria/

Sameeer Joshi, “Drone Swarms: The Next Evolution in Warfare”, Raksha Anirveda, 2021, raksha-anirveda.com/drone-swarms-the-next-evolution-in-warfare/

SIPRI, Sipri Military Expenditure Database, sipri.org

Tatevik Hayrapetyan, “How Ilham ‘Personalizes’ the Results of the 2020 Artsakh War”, ENV Report, 2021, evnreport.com/politics/how-ilham-aliyev-personalizes-the-results-of-the-2020-artsakh-war/

Burak Ege Bekdil, “Azerbaijan to Buy Armed Drones from Turkey”, Defense News, 2020, defensenews.com/unmanned/2020/06/25/azerbaijan-to-buy-armed-drones-from-turkey/

Itamildar, “Turkish ‘Hawk’ Deployed in Tripoli”, Italmidar, 2020, itamilradar.com/2020/01/18/turkish-hawk-deployed-in-tripoli/

John V. Parachini and Peter A. Wilson, “Drone-Era Warfare Shows the Operational Limits of Air Defense Systems”, RAND Corporation, 2020, rand.org/blog/2020/07/drone-era-warfare-shows-the-operational-limits-of-air.html

Bethan McKernan, “Trench warfare, drones and cowering civilians: on the ground in Nagorno-Karabakh”, The Guardian, 2020, theguardian.com/artanddesign/2020/oct/13/trench-warfare-drones-and-cowering-civilians-on-the-ground-in-nagorno-karabakh

BBC News, “Ukraine conflict: How are drones being used?”, 2022, bbc.com/news/world-62225830

Ellen Nakashima and Joby Warrick, “Iran sends first of drones to Russia for use in Ukraine”, The Washington Post, 2022, washingtonpost.com/national-security/2022/08/29/iran-drones-russia-ukraine-war/

Stephen Witt, “The Turkish Drone That Changed The Nature of Warfare”, TheNewYorker, 2022, newyorker.com/magazine/2022/05/16/the-turkish-drone-that-changed-the-nature-of-warfare

David Axe, “After Five Months Russia Finally Managed to Destroy Some Ukranian Drone Equipment”, Forbes, 2022, forbes.com/sites/davidaxe/2022/07/28/after-five-months-the-russians-finally-managed-to-destroy-some-ukrainian-drone-equipment/?sh=40f4db7a1aea

Oryx Database, last seen September 2022, oryxspioenkop.com/2022/02/attack-on-europe-documenting-equipment.html

Illia Ponomarenko, “Why Ukraine struggles to fight Russia’s artillery superiority”, The Kyiv Independent, 2022, kyivindependent.com/national/why-ukraine-struggles-to-combat-russias-artillery-superiority

Joe Gould, “US weapons package for Ukraine stresses long-haul commitment”, Defense News, 2022, defensenews.com/pentagon/2022/08/24/us-to-send-ukraine-anti-air-anti-drone-systems-as-war-hits-milestone/

David A. Fulghum, “RQ-170 Has Links To Intelligence Loss to China”, Aviation Week, 2009, web.archive.org/web/20121016142710/http://www.aviationweek.com/Blogs.aspx?plckBlogId=Blog:27ec4a53-dcc8-42d0-bd3a-01329aef79a7&plckController=Blog&plckBlogPage=BlogViewPost&newspaperUserId=27ec4a53-dcc8-42d0-bd3a-01329aef79a7&plckPostId=Blog:27ec4a53-dcc8-42d0-bd3a-01329aef79a7Post:7544751e-3bdc-4e52-9be7-07000988da92&plckScript=blogScript&plckElementId=blogDest

David A. Fulghum, “U.S. AirForce Reveals Operational Stealth UAV”, Aviation Week, 2009, web.archive.org/web/20111117090945/http://www.aviationweek.com/aw/blogs/defense/index.jsp?plckController=Blog&plckBlogPage=BlogViewPost&newspaperUserId=27ec4a53-dcc8-42d0-bd3a-01329aef79a7&plckPostId=Blog%3a27ec4a53-dcc8-42d0-bd3a-01329aef79a7Post%3a649e3cf4-8c07-4739-82cf-322c6c56ccd5&plckScript=blogScript&plckElementId=blogDest

Bill Sweetman, “The Beast is Back”, Aviation Week, 2011, https://web.archive.org/web/20111117085419/http://www.aviationweek.com/aw/blogs/defense/index.jsp?plckController=Blog&plckBlogPage=BlogViewPost&newspaperUserId=27ec4a53-dcc8-42d0-bd3a-01329aef79a7&plckPostId=Blog%3a27ec4a53-dcc8-42d0-bd3a-01329aef79a7Post%3a5b32f70f-3054-4261-947e-dc8fe095d08b&plckScript=blogScript&plckElementId=blogDest

Scott Shane and David E. Sanger, “Drone Crash in Iran Reveals Secret U.S Surveillance Effort”, The New York TImes, 2011, nytimes.com/2011/12/08/world/middleeast/drone-crash-in-iran-reveals-secret-us-surveillance-bid.html

Lock-Heed Martin, ISR & Unmanned Systems, lockheedmartin.com/en-us/who-we-are/business-areas/aeronautics/skunkworks.html

David Hambling, “Mysteries Surrounding Afghanistan’s Stealth Drone (Updated)”, Wired, 2009, wired.com/2009/12/mysteries-surround-afghanistans-stealth-drone/

BAE Systems, www.baesystems.com/en-uk/product/taranis1

Paul Marks, “Warning Sounded Over British Dogfighting Drone”, New Scientist, 2010, newscientist.com/article/dn19162-warning-sounded-over-british-dogfighting-drone/?ignored=irrelevant

Online News Room, “BAE Systems to to lead £124 milion UAV Technology Demonstration Programme”, 2006, web.archive.org/web/20070613033420/http://147.29.80.132/newsroom/2006/dec/071206news1.htm

Dan Sabbagh, Killer Drones: how many there are out there and who do they target?”, The Guardian, 2019, theguardian.com/news/2019/nov/18/killer-drones-how-many-uav-predator-reaper

Luca Peruzzi, “Italy flies first Predator B sortie over Libya”, Flight Global, 2011, flightglobal.com/italy-flies-first-predator-b-sortie-over-libya/101538.article

Cap. Roberto Berardi, “Kosovo: primo volo del Predator”, Aeronautica Militare, 2012, web.archive.org/web/20150206223036/http://www.aeronautica.difesa.it/News/Pagine/KosovobattesimodelvolodelPredator.aspx

Tom Sheve, “How the MQ-9 Reaper Works”, HowStuffWorks, science.howstuffworks.com/reaper.htm

Lock-Heed Martin, “Media Kit: F-35 A Information”, lastly updated september 2022, f35.com/content/dam/lockheed-martin/aero/f35/documents/FG19-00608_001 Product Card F-35A media.pdf

U.S. Air Force, “F-35 Refueling”, 2013, af.mil/News/Photos/igphoto/2000048079/

Valerie Insinna and David B. Larter, “Supersonic speed could cause big problems for the F-35’s stealth coating”, Defense News, 2020, defensenews.com/air/2019/06/12/supersonic-speeds-could-cause-big-problems-for-the-f-35s-stealth-coating/

Executive Flyers, “How Long Does It Take to Refuel a Plane?”, 2022, executiveflyers.com/how-long-does-it-take-to-refuel-a-plane/

Rich Abbott, “New Demonstration Shows F-35’s Data Sharing Capability”, Aviation Today, 2019, aviationtoday.com/2019/08/08/82484/

Paul C. Cabellon, “Northrop Grumman Distributed Aperture System (DAS) for F-35 Demonstrates Ballistic Missile Defense Capabilities”, Northrop Grumman, 2010, news.northropgrumman.com/news/releases/photo-release-northrop-grumman-distributed-aperture-system-das-for-f-35-demonstrates-ballistic-missile-defense-capabilities

Jon Lake, “AESA does it… or does it?”, Times Aerospace, timesaerospace.aero/features/defence/aesa-does-itor-does-it

Shishir Gupta, “India develops AESA radar to make IAF more lethal”, Hindustan Times, 2021, hindustantimes.com/india-news/iaf-to-showcase-use-of-indigenous-aesa-radar-101638924141445.html

Military.com, “AGM-154 Standoff Weapon”, military.com/equipment/agm-154-joint-standoff-weapon

Peter Sociu, “Why Does the F-35 Stealth Fighter Need a Gun? One Word: History”, The National Interest, 2021, nationalinterest.org/blog/buzz/why-does-f-35-stealth-fighter-need-gun-one-word-history-179562

Daniel Patrascu, “Inverted F-35 Lighting Fires Flares for First Time in Public, Looks Ready for War”, Autoevolution, 2021, autoevolution.com/news/inverted-f-35-lightning-fires-flares-for-first-time-in-public-looks-ready-for-war-173378.html

Lock-Heed Martin, “10 Ways the F-35 Simulator is Changing Pilot Training”, 2021, .f35.com/f35/news-and-features/10-ways-the-f35-simulator-is-changing-pilot-training.html

David B. Larter and Valerie Insinna, “The Pentagon will have to live with limits on F-35’s supersonic flights”, Defense News, 2020, defensenews.com/air/2020/04/24/the-pentagon-will-have-to-live-with-limits-on-f-35s-supersonic-flights/

US Air Force, “MQ-9 Reaper”, last updated 2021, af.mil/About-Us/Fact-Sheets/Display/Article/104470/mq-9-reaper/

Alex Hollings, “Can The Military Save This Deadly Terrorist Hunter from the Scrap Heap?”, Popular Mechanics, 2021, www.popularmechanics.com/military/a37623821/the-end-of-the-mq-9-reaper/

US Air Force, “MQ-9 Reaper”, last updated 2021, af.mil/About-Us/Fact-Sheets/Display/Article/104470/mq-9-reaper/
Military.com, “AGM 114-Hellfire”, military.com/equipment/agm-114-hellfire

General Atomics, “New Block 50 Ground Stations Flies MQ-9 Reaper”, 2019, ga-asi.com/new-block-50-ground-control-station-flies-mq-9-reaper

Winslow Wheeler, “2. The MQ-9 Cost and Performance, TIME, 2012, nation.time.com/2012/02/28/2-the-mq-9s-cost-and-performance/