Why Drones Have Not Revolutionized War

The Enduring Hider-Finder Competition in Air Warfare

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Over the past two decades, unmanned aerial vehicles (UAVs) have progressively become a constant feature of modern conflicts and, if current trends continue, they will likely become even more important in the future.[1] Substituting troops with various types of robotic systems on the ground, in the air, and at sea raises major ethical, legal, and philosophical questions.[2] Equally important are the implications for international security: Some scholars believe, for instance, that drone technology could unleash an "unmanned revolution in military affairs," which would affect not only military doctrine, organization, and force structure but also regional and international stability.[3] According to the conventional wis-

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1. Matthew Fuhrmann and Michael C. Horowitz, "Droning On: Explaining the Proliferation of Unmanned Aerial Vehicles," *International Organization*, Vol. 71, No. 2 (2017), pp. 397–418, https://doi.org/10.1017/S0020818317000121.
2. P.W. Singer, *Wired for War: The Robotics Revolution and Conflict in the 21st Century* (New York: Penguin, 2009); Christopher Coker, *Warrior Geeks: How 21st Century Technology is Changing the Way We Fight and Think about War* (London: Hurst, 2013); Peter L. Bergen and Daniel Rothenberg, eds., *Drone Wars: Transforming Conflict, Law, and Policy* (Cambridge: Cambridge University Press, 2014); Hugh Gusterson, *Drone: Remote Control Warfare* (Cambridge: Massachusetts Institute of Technology Press, 2016); and Michael J. Boyle, *The Drone Age: How Drone Technology Will Change War and Peace* (Oxford: Oxford University Press, 2020).
3. Adam N. Stulberg, "Managing the Unmanned Revolution in the U.S. Air Force," *Orbis*, Vol. 51, No. 2 (2007), pp. 251–265, https://doi.org/10.1016/j.orbis.2007.01.005; and Stephen Bryen, "Armed Drones Revolutionizing the Future of War," *Asia Times*, December 9, 2020, https://asiatimes.com/2020/12/armed-drones-revolutionizing-the-future-of-war/. See also Jürgen Altmann and Frank Sauer, "Autonomous Weapon Systems and Strategic Stability," *Survival*, Vol. 59, No. 5 (2017), pp. 117–142, https://doi.org/10.1080/00396338.2017.1375263.

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dom, drones are considered revolutionary because of three direct effects that they exert on military conflict and world politics. First, given their small size and other features, military drones are supposedly more effective at avoiding or limiting detection by modern radars compared with traditional military aircraft. Drones can thus more easily penetrate enemy air defense systems, which in turn favors offensive military operations. Second, the conventional wisdom holds that the affordable cost and technological unsophistication of drones lower the entry barriers for acquiring advanced military capabilities. By canceling or reducing existing asymmetries in military power, drones can thus strengthen militarily weaker and resource-scarce actors. Finally, some believe that UAVs, by making long-range precision strikes more accessible, will eliminate close combat from the battlefield, which would relieve states from the need to deploy ground troops.[4]

For many experts, recent conflicts corroborate the revolutionary effects of UAVs. Some, for instance, describe drones in the 2020 Nagorno-Karabakh war as a "magic bullet" or a "tactical game changer."[5] Echoing these views, the *Wall Street Journal* suggests that drones are "reshap[ing] battlefields and geopolitics."[6] The German Institute for Defense and Strategic Studies concludes that German armed forces "would have hardly stood a chance" against an adversary equipped with military drones, such as Azerbaijan in the 2020 Nagorno-Karabakh war.[7] Agnes Callamard and James Rogers go even further and maintain that the proliferation of increasingly capable drones will soon "help decide the fate of nations."[8]

4. T. X. Hammes, "Droning America: The Tech Our Enemies Can Buy," *War on the Rocks*, October 8, 2013, https://warontherocks.com/2013/10/droning-america-the-tech-our-enemies-can-buy/; Noel Sharkey, "Drone Race Will Ultimately Lead to a Sanitized Factory of Slaughter," *Guardian*, August 3, 2012, https://www.theguardian.com/world/2012/aug/03/drone-race-factory-slaughter; and Sarah Kreps and Micah Zenko, "The Next Drone Wars: Preparing for Proliferation," *Foreign Affairs*, Vol. 93, No. 2 (March/April 2014), pp. 68–79, https://www.foreignaffairs.com/articles/2014-02-12/next-drone-wars.
5. Cited in David Hambling, "The 'Magic Bullet' Drones behind Azerbaijan's Victory over Armenia," *Forbes*, November 10, 2020, https://www.forbes.com/sites/davidhambling/2020/11/10/the-magic-bullet-drones-behind—azerbaijans-victory-over-armenia/; and Arshaluys Mgdesyan, "Drones A Game Changer in Nagorno-Karabakh," *Eurasia Review*, November 2, 2020, https://www.eurasiareview.com/02112020-drones-a-gamechanger-in-nagorno-karabakh/.
6. James Marson and Brett Forrest, "Armed Low-Cost Drones, Made by Turkey, Reshape Battlefields and Geopolitics," *Wall Street Journal*, June 3, 2021, https://www.wsj.com/articles/armed-low-cost-drones-made-by-turkey-reshape-battlefields-and-geopolitics-11622727370.
7. "Bundeswehr nicht gegen Angriffe von Kampfdrohnen gerüstet" [German armed forces not prepared against attacks by combat drones], *Die Zeit* [The Time], June 13, 2021, https://www.zeit.de/news/2021-06/13/analyse-bundeswehr-gegen-drohnen-unterlegen.
8. Agnes Callamard and James Rogers, "We Need a New International Accord to Control Drone Proliferation," *Bulletin of Atomic Scientists*, December 1, 2020, https://thebulletin.org/2020/12/we-need-a-new-international-accord-to-control-drone-proliferation/.

If we are at the outset of the drone revolution, world politics will change dramatically in the near future. Were drones to lower the entry barrier for acquiring and employing advanced military capabilities, century-old links between wealth and power might weaken or disappear. Consequently, a "new medievalism" may emerge, in which a multitude of state and non-state actors can wage large-scale wars.[9] Additionally, more widespread military power may entail more instability and conflict. As Amy Zegart notes, "because drones carry dramatically lower human and financial costs," they make it more politically feasible for states to "'keep shooting forever,'" thereby threatening enduring peace.[10] Finally, if a drone revolution is in the making, states will have to significantly revise their defense policies. Ian Shaw maintains, for instance, that "large-scale ground wars are being eclipsed by fleets of weaponised drones."[11] Similarly, Francis Fukuyama suggests that "the use of drones is going to change the nature of land power," thus "undermin[ing] existing force structures."[12] T. X. Hammes further argues that "many states, and even insurgent or terrorist groups, will be able to project force at intercontinental range," and as a result, "opponents will have an increased ability to threaten intermediate [U.S.] bases."[13] Accordingly, the global-reach defense posture of the United States, which uses forward-deployed troops and capabilities, will become increasingly vulnerable and all states will have to restructure their armed forces away from expensive and complex military platforms in favor of new, less sophisticated, and cheaper technologies such as drones.[14]

These concerns are legitimate, especially in light of the unprecedented technological transformation that is unfolding.[15] Yet, as Stephen Biddle noted al-

9. On new medievalism, see Hedley Bull, *The Anarchical Society: A Study of Order in World Politics*, 3rd ed. (Basingstoke: Palgrave, 2002), pp. 245–246; and Ian Sullivan, "The Myth of Agincourt and Lessons on Army Modernization," *Mad Scientist Laboratory* blog, July 25, 2019, https://madsciblog.tradoc.army.mil/164-the-myth-of-agincourt-and-lessons-on-army-modernization/.
10. Amy Zegart, "Cheap Fights, Credible Threats: The Future of Armed Drones and Coercion," *Journal of Strategic Studies*, Vol. 43, No. 1 (2020), p. 18, https://doi.org/10.1080/01402390.2018.1439747.
11. Ian G. R. Shaw, "Predator Empire: The Geopolitics of US Drone Warfare," *Geopolitics*, Vol. 18, No. 3 (2013), pp. 536–559, https://doi.org/10.1080/14650045.2012.749241.
12. Francis Fukuyama, "Droning On in the Middle East," *American Purpose*, April 5, 2021, https://www.americanpurpose.com/blog/fukuyama/droning-on/.
13. T. X. Hammes, *Technologies Converge and Power Diffuses: The Evolution of Small, Smart, and Cheap Weapons*, Policy Analysis 786 (Washington, D.C.: CATO Institute, January 2016), https://www.cato.org/policy-analysis/technologies-converge-power-diffuses-evolution-small-smart-cheap-weapons#loss-of-immunity-to-attack.
14. T. X. Hammes, "In an Era of Cheap Drones, US Can't Afford Exquisite Weapons," *Defense One*, January 19, 2016, https://www.defenseone.com/ideas/2016/01/cheap-drones-exquisite-weapons/125216/; and T. X. Hammes, "An End to Exquisite Weapons," *National Interest*, July 26, 2020, https://nationalinterest.org/blog/skeptics/end-exquisite-weapons-165488.
15. Erik Brynjolfsson and Andrew McAfee, *The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies* (New York: W.W. Norton, 2014).

most twenty years ago about the debate on the revolution in military affairs, "change, of course, is inevitable. But so is continuity. And today's policy debate systematically exaggerates the former and slights the latter."[16] As we explain in this article, Biddle's considerations also apply to the drone revolution in military affairs. Analysts, policymakers, and scholars who have analyzed and discussed drones have generally neglected a constant that has defined air warfare since at least the 1960s—its unforgiving lethality and its implications for modern military operations. We develop a theoretical framework according to which the lethality of air warfare has led to a "hider-finder" competition between air defense and air penetration.[17] This competition imposes high costs on those who fail to master the set of tactics, techniques, procedures, technologies, and capabilities necessary to limit exposure to enemy fire and to detect enemy targets—borrowing on Biddle's work, we call it the modern system of force employment in air warfare.[18] Rather than representing a rupture with the past, our framework suggests that drones are part of the evolution of air warfare, whose fundamental principle remains to avoid exposure to enemy fire. We maintain that drones do not by themselves produce the revolutionary effects that many have attributed to them. Specifically, drones are unlikely to shift the offense-defense balance toward the offense because they are vulnerable to electronic warfare and air defense systems. Drones are also unlikely to cancel existing military asymmetries because they require support from expensive and complex military assets as well as highly trained personnel. Finally, drones are unlikely to eliminate close combat and erase the importance of skills and proficiency in modern warfare because of opportunities to conceal ground capabilities.

Despite its wide acceptance, proponents of the drone revolution have used

16. Stephen Biddle, *Military Power: Explaining Victory and Defeat in Modern Battle* (Princeton, N.J.: Princeton University Press, 2004), p. ix.
17. Our understanding of the hider-finder competition in the air domain is inspired by the dynamics in submarine warfare as explained by Owen R. Cote Jr., *The Third Battle: Innovation in the U.S. Navy's Silent Cold War Struggle with Soviet Submarines* (Newport, R.I.: Naval War College Press, 2009), p. 48. For a discussion of this competition in the air domain, see Frank Heilenday, *Principles of Air Defense and Air Vehicle Penetration* (Washington, D.C.: George Washington University, 1988). The hider-finder competition is the competition between innovations, countertactics, countermeasures, and counter-innovations in the age of advanced sensors. Bernard Brodie and Fawn M. Brodie, *From Crossbow to H-Bomb: The Evolution of the Weapons and Tactics of Warfare* (Bloomington: Indiana University Press, 1973), pp. 6, 137, 178; and Kenneth Macksey, *Technology in War: The Impact of Science on Weapon Development and Modern Battle* (New York: Prentice Hall, 1986), pp. 34–35.
18. James R. Brungess, *Setting the Context: Suppression of Enemy Air Defenses and Joint War Fighting in an Uncertain World* (Maxwell Air Force Base, Ala.: Air University Press, 1994); John A. Tirpak, "Dealing with Air Defense," *Air Force Magazine*, November 1999, pp. 25–29, https://www.airforcemag.com/PDF/MagazineArchive/Documents/1999/November%201999/1199airdefense.pdf; and Carlo Kopp, "Evolving Technological Strategy in Advanced Air Defense Systems," *Joint Force Quarterly*, No. 57 (April 2010), pp. 86–93.

only anecdotal or fragmented evidence to support their claims, and they have not yet offered a systematic assessment.[19] We fill this gap by testing the postulates of the drone revolution thesis against the hypotheses that we derive from our framework on three recent conflicts in which UAVs were used extensively: the Western Libya military campaign of the second Libyan civil war (2019–2020), the Syrian civil war (2011–2021), and the Armenia-Azerbaijan conflict over Nagorno-Karabakh (2020).[20] Methodologically, these cases feature significant within-case and cross-case variation for key independent variables (e.g., availability of air defense systems and electronic warfare systems, as well as personnel skills and combat proficiency). Despite being hailed as paradigmatic examples of the ensuing drone revolution in military affairs, these cases do not support this dominant narrative. In contrast, our findings confirm the validity of the modern system of force employment and highlight the importance of proficient personnel as well as electronic warfare and air defense systems, factors that are often neglected in public and political debates surrounding drones. In comparison to Biddle's analysis of land warfare, ours shows that, in air warfare, the modern system depends much more on technology.[21]

We derive two key policy recommendations from our analysis. First, available data suggests that the supposed revolutionary effects of drones are at least premature and possibly exaggerated. Policymakers should hence be cautious about calls for radical changes in force structure and defense posture. Second, our analysis indicates that a regional or great power may be able to rebalance an ongoing, drone-intensive conflict by providing its local allies with air defense systems, electronic warfare systems, and skilled military personnel.

Conventional Wisdom about Drone Warfare

Over the past two decades, armed drones and their employment in military operations have attracted growing attention from analysts, practitioners, and

19. For an exception, see Heiko Borchert, Torben Schütz, and Joseph Verbovszky, *Beware the Hype: What Military Conflicts in Ukraine, Syria, Libya, and Nagorno-Karabakh (Don't) Tell Us about the Future of War* (Hamburg, Germany: Defense AI Observatory, 2021), https://defenseai.eu/daio_beware_the_hype.
20. In this paper we focus on medium-altitude long-endurance (MALE) drones that belong to the Class III of the *The Drone Databook*, which assigns a classification ranging from I to III to drones largely on the basis of their maximum takeoff weight: Class I (less than 150 kilograms), Class II (150 to 600 kilograms), and Class III (more than 600 kilograms). See Dan Gettinger, *The Drone Databook* (Annandale-on-Hudson, N.Y.: Center for the Study of the Drone, Bard College, 2019), p. v, https://dronecenter.bard.edu/files/2019/10/CSD-Drone-Databook-Web.pdf.
21. For a similar point, see Eliot A. Cohen, "Stephen Biddle on Military Power," *Journal of Strategic Studies*, Vol. 28, No. 3 (June 2005), pp. 413–424, https://doi.org/10.1080/01402390500137259.

scholars from different traditions. Yet, rather than empirically investigating the tactical and operational effects of UAVs, most authors have assumed that these effects exist. Starting from these assumptions, they have then derived the strategic, political, and ontological implications of drone warfare.[22]

DRONE REVOLUTION PROPONENTS

According to the accepted wisdom, drones represent a major turning point in warfare.[23] P. W. Singer, for instance, notes that "increasingly, unmanned systems are becoming a game changer."[24] James Rogers argues that drones, like gunpowder, have been the most significant development in the history of weaponry.[25] Similarly, Tim Hsia and Jared Sperli believe that robotics will be the first revolution "in military affairs of the 21st century."[26] This drone revolution narrative builds on three key effects that drones are supposed to exert. First, drones allegedly yield an offensive advantage because they can penetrate modern air defense systems.[27] Whereas some scholars have not substantiated this assumption, others have explicitly argued that traditional air defense systems struggle to detect drones because of their small size as well as their capacity to fly at low altitude and at slow speed.[28]

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22. Studies on the effects of drones in counterinsurgency operations represent an exception to this problem. See, for example, Asfandyar Mir, "What Explains Counterterrorism Effectiveness? Evidence from the U.S. Drone War in Pakistan," *International Security*, Vol. 43, No. 2 (Fall 2018), pp. 45–83, https://doi.org/10.1162/isec_a_00331.
23. Singer, *Wired for War*; and Coker, *Warrior Geeks*.
24. Quoted in Declan Walsh, "Foreign Drones Tip the Balance in Ethiopia's Civil War," *New York Times*, December 20, 2021, https://www.nytimes.com/2021/12/20/world/africa/drones-ethiopia-war-turkey-emirates.html.
25. James Rogers, "What Has Been the Most Significant Development in the History of Weaponry?" *BBC History Magazine*, October 2020, p. 41.
26. Tim Hsia and Jared Sperli, "How Cyberwarfare and Drones Have Revolutionized Warfare," *At War* blog, *New York Times*, June 17, 2013, https://atwar.blogs.nytimes.com/author/tim-hsia-and-jared-sperli/.
27. Michael Mayer, "The New Killer Drones: Understanding the Strategic Implications of Next-Generation Unmanned Combat Aerial Vehicles," *International Affairs*, Vol. 91, No. 4 (July 2015), p. 774, https://doi.org/10.1111/1468-2346.12342; and Rogers, "What Has Been the Most Significant Development in the History of Weaponry?," p. 41.
28. Sarah Kreps and Sarah Maxey, "Context Matters: The Transformative Nature of Drones on the Battlefield," in Giampiero Giacomello, Francesco N. Moro, and Marco Valigi, eds., *Technology and International Relations: The New Frontier in Global Power* (Cheltenham, UK: Edward Elgar, 2021), p. 80; James Cavallaro, Stephan Sonnenberg, and Sarah Knuckey, *Living Under Drones: Death, Injury and Trauma to Civilians from US Drone Practices in Pakistan* (Stanford, Calif.: International Human Rights and Conflict Resolution Clinic, Stanford Law School, 2012; New York: NYU School of Law, Global Justice Clinic, 2012), pp. 140–141, https://law.stanford.edu/publications/living-under-drones-death-injury-and-trauma-to-civilians-from-us-drone-practices-in-pakistan/; Boyle, *The Drone Age*, pp. 152, 167; John V. Parachini and Peter A. Wilson, "Drone-Era Warfare Shows the Operational Limits of Air Defense Systems," *RealClearDefense*, July 2, 2020, https://www.realcleardefense.com/articles/2020/07/02/drone-era_warfare_shows_the_operational_limits_of_air_defense_systems_115430.html; and D. B. Des Roches, "The Siren Song of the Drone:

Second, because of UAVs' allegedly low cost and limited sophistication, many observers maintain that drones lower the entry barriers for modern military operations and hence are an equalizing force between major and minor military actors.[29] By decoupling economic (and industrial) might and military power, drones may thus become the "poor man's air force" and allow resource-scarce actors to acquire, develop, and employ advanced military capabilities.[30]

Third, some believe that drones may permit states to fight from standoff positions without deploying troops on the ground.[31] By eradicating "distance" from the modern battlefield, drones would make close combat obsolete, remove physical barriers to unlimited projection of power, and "nullify the twentieth-century belief in 'boots on the ground' as a proxy-war necessity."[32] Together, these three presumed effects explain the significant attention that the diffusion of drones has received over the past two decades.[33]

DRONE REVOLUTION SKEPTICS

Some scholars question the drone revolution thesis, pointing out that only wealthy and militarily powerful states can use drones effectively in military operations because they require complementary support, primarily in terms of command, control, and communications infrastructure.[34] Others highlight that current-generation drones are vulnerable to modern air defenses, which

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Understanding the Factors Driving GCC Drone Acquisition," *Al Jazeera Centre for Studies*, May 1, 2021, https://studies.aljazeera.net/en/analyses/siren-song-drone-understanding-factors-driving-gcc-drone-acquisition.

29. Keith Hayward, *Unmanned Aerial Vehicles: A New Industrial System* (London: Royal Aeronautical Society, November 2013).

30. Nick Waters, "The Poor Man's Air Force? Rebel Drones Attack Russia's Airbase in Syria," *Bellingcat*, January 12, 2018, https://www.bellingcat.com/news/mena/2018/01/12/the_poor_mans_airforce/.

31. Derek Gregory, "From a View to a Kill: Drones and Late Modern War," *Theory, Culture & Society*, Vol. 28, No. 7 (Winter 2012), pp. 188–215, https://doi.org/10.1177/0263276411423027; Shaw, "Predator Empire"; and Fukuyama, "Droning On in the Middle East."

32. Andrew Mumford, "Proxy Warfare and the Future of Conflict," *RUSI Journal*, Vol. 158, No. 2 (2013), p. 43, https://doi.org/10.1080/03071847.2013.787733.

33. Micah Zenko and Sarah Kreps, *Limiting Armed Drone Proliferation* (Washington, D.C.: Council on Foreign Relations Press, June 2014); and Allen Buchanan and Robert O. Keohane, "Toward a Drone Accountability Regime," *Ethics & International Affairs*, Vol. 29, No. 1 (Spring 2015), pp. 15–37, https://doi.org/10.1017/S0892679414000732.

34. Shashank Joshi and Aaron Stein, "Emerging Drone Nations," *Survival*, Vol. 55, No. 5 (2013), pp. 53–78, https://doi.org/10.1080/00396338.2013.841805; Austin Long, "Dueling Asymmetries: International Terrorism, Insurgency, and Drone Warfare in the 21st Century," in *The Future of Warfare in the 21st Century* (Abu Dhabi: Emirates Center for Strategic Studies and Research, 2014), pp. 13–36; and Andrea Gilli and Mauro Gilli, "The Diffusion of Drone Warfare? Industrial, Organizational, and Infrastructural Constraints," *Security Studies*, Vol. 25, No. 1 (2016), pp. 50–84, http://dx.doi.org/10.1080/09636412.2016.1134189.

makes them unlikely candidates for conventional conflicts against capable states.[35] But this scholarship has failed to address some key aspects in the debate about drones.

First, these scholars have accepted but not investigated some central claims—such as the vulnerability of drones to modern air defense systems. This is particularly important not only because the drone revolution proponents advance the opposite proposition, but also because some skeptics have changed their views on this issue.[36] Similarly, some skeptics have changed their positions on the infrastructural requirements of drones operations as well.[37] Additionally, in recent conflicts such as in Libya and Nagorno-Karabakh, current-generation drones were successfully employed in conventional settings, in contrast to some skeptics' expectations. Finally, scholars who have noted the vulnerability of current-generation drones to modern air defense systems have considered drones in isolation and not in combined arms operations, thus prompting the question of whether and to what extent combat skills and supporting assets can overcome the technological limitations of current-generation drones.

The Modern System of Force Employment in Air Warfare

To understand the effectiveness of military drones, we advance a theory that builds on Stephen Biddle's modern system of force employment, and we adapt it to air warfare.[38]

THE EVOLUTION OF THE FIREPOWER REVOLUTION

The starting point of Biddle's analysis is the firepower revolution that took place shortly before World War I, when a set of technological changes in gun manufacturing dramatically increased the rate, volume, and precision of firepower.[39] Exposure to radical firepower became lethal, and troops were forced to devise new solutions to advance on the battlefield. These solutions

35. Gilli and Gilli, "The Diffusion of Drone Warfare?" p. 80; and Michael C. Horowitz, Sarah E. Kreps, and Matthew Fuhrmann, "Separating Fact from Fiction in the Debate over Drone Proliferation," *International Security*, Vol. 41, No. 2 (Fall 2016), p. 26, https://doi.org/10.1162/ISEC_a_00257.
36. Compare views on the vulnerability of drones to air defense systems in Kreps and Maxey, "Context Matters," p. 80; and Horowitz, Kreps, and Fuhrmann, "Separating Fact from Fiction in the Debate over Drone Proliferation," p. 16.
37. Compare views on the infrastructural support that drones require in John Kaag and Sarah Kreps, *Drone Warfare* (Hoboken, N.J.: Wiley, 2014), p. 148; and Zenko and Kreps, *Limiting Armed Drone Proliferation*, p. x.
38. Biddle, *Military Power.*
39. Ibid., p. 3.

are what Biddle calls the modern system of force employment, a set of tactics and procedures entailing "cover, concealment, dispersion, suppression, small-unit independent maneuver and combined arms at the tactical level," as well as "depth, reserves, and differential concentration at the operational level of war."[40] These techniques, Biddle contends, "sharply reduce vulnerability to even twenty-first century weapons and sensors."[41] Whether states have mastered the modern system explains victory and defeat in modern (land) warfare throughout the twentieth century and beyond.[42]

We maintain that, starting from the 1960s, a second firepower revolution has dramatically increased the lethality of air warfare for both air penetration and air defense.[43] This second firepower revolution is part of what the late Gen. William DePuy called the era of "new lethality" in which "what we see we can hit; what we hit we can kill."[44] It is the result of concomitant developments in electronics, materials, and propulsion that have brought about dramatic improvements in detection, communication, precision, and destruction.[45] The resulting unforgiving lethality, in turn, has led to a hider-finder competition between air forces and air defenses, which entails hiding from enemy sensors while finding enemy targets.[46] This hider-finder competition rewards those who can masterfully employ the tactics, techniques, procedures,

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40. Ibid., pp. 3, 28.
41. Ibid., p. 3.
42. Ibid., pp. 150–180.
43. Lon O. Nordeen, *Air Warfare in the Missile Age* (Washington, D.C.: Smithsonian Institution Press, 1985); Michael Russell Rip and James M. Hasik, *The Precision Revolution: GPS and the Future of Aerial Warfare* (Annapolis, Md.: Naval Institute Press, 2002); and Barry D. Watts, *Six Decades of Guided Munitions and Battle Networks: Progress and Prospects* (Washington, D.C.: Center for Strategic and Budgetary Assessments [CSBA], 2007).
44. Dwight E. Phillips Jr., *Reengineering Institutional Culture and the American Way of War in the Post-Vietnam U.S. Army, 1968–1989*, Ph.D. dissertation, University of Chicago, 2014, p. 59, cited in Stephen Robinson, *The Blind Strategist: John Boyd and the American Art of War* (Dunedin, New Zealand: Exisle, 2021), p. 26.
45. The first sign of this transformation was the shooting down of the U2 Lady Hawk in 1960 by the Soviet S-75 Dvina (NATO reporting name SA-2 Guideline), which made high-altitude flight no longer sufficient to defeat enemy air defenses. Steven J. Zaloga, "Defending the Capitals: The First Generation of Soviet Strategic Air Defense Systems 1950–1960," *Journal of Slavic Military Studies*, Vol. 10, No. 4 (October 1997), pp. 30–43. The subsequent use of Soviet surface-to-air missiles in Vietnam (with the shooting down of the United States' long-range strategic bomber, the B-52 Stratofortress) and in the Middle East further confirmed the beginning of the new era in air warfare (Israel lost fifty aircraft in the first three days of the 1973 Arab-Israeli War and about seventy-eight to ninety aircraft in the first week). See Anthony H. Cordesman and Abraham R. Wagner, *The Lessons of Modern War: Volume 1: The Arab-Israeli Conflicts, 1973–1989* (Boulder, Colo.: Westview, 1990), pp. 18–23; and Kenneth P. Werrell, *Archie to SAM: A Short Operational History of Ground-Based Air Defense* (Maxwell Air Force Base, Ala.: Air University Press, 2005), p. 152.
46. Heilenday, *Principles of Air Defense and Air Vehicle Penetration*, pp. 9.1–9.20. For a specific discussion of the hider-finder competition during the Battle of Britain, see Jon R. Lindsay, *Information Technology and Military Power* (Ithaca, N.Y.: Cornell University Press, 2020), pp. 71–108.

technologies, and capabilities that limit exposure to enemy fire while successfully detecting and targeting the enemy. In comparison to land warfare, the modern system of force employment is much more challenging in air warfare, for both air defense and even more for air penetration. In the next sections, we explain why this is the case.

THE MODERN SYSTEM FOR AIR DEFENSE

Air defense must detect, locate, identify, track, and, if needed, engage intruders, while avoiding being degraded by an enemy's cyber and electronic countermeasures (e.g., hacking, jamming, or spoofing) and being targeted by an enemy's suppression of enemy air defense assets.[47] Detecting targets while avoiding detection is very challenging for two sets of reasons.

THE CHALLENGE OF AIR DEFENSE. As Biddle explains, in land warfare, the modern system of force employment is extremely difficult and demanding, as it requires skilled and proficient military personnel to carry out a multitude of complex and coordinated tasks in a strict and time-sensitive sequence. For air defense, the modern system is even more difficult than in land warfare.[48] To start, opportunities for cover are much more limited for ground-based air defenses because of the difference in elevation with penetrating aircraft. Whereas irregularities in the terrain such as trenches and gullies shield troops on the ground from direct firepower, they lose most of their effectiveness against air-to-ground guided munitions.[49]

Moreover, concealment is inherently more difficult for air defense than for ground troops tasked with defending a given territory. For air defense to detect and track incoming aerial intruders, radars need to actively search the sky, which inevitably exposes the position of the antenna emitting electro-magnetic signals.[50] Additionally, air defense systems are difficult to conceal even when

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47. Heilenday, *Principles of Air Defense and Air Vehicle Penetration*, pp. 1.1–1.5; *Electronic Warfare Fundamentals* (Nellis Air Force Base, Nev.: Air Combat Command Training Support Squadron, 2000), pp. 1.6–1.10; and Justin Bronk, "Modern Russian and Chinese Integrated Air Defence Systems: The Nature of the Threat, Growth Trajectory, and Western Options" (London: Royal United Services Institute for Defence and Security Studies, January 2020).
48. Air defense can be divided into passive and active measures. Passive air defense includes camouflage, concealment, deception, dispersion, reconstitution, redundancy, detection, warning systems, and the use of protective construction. Active air defense includes air defense weapons, electronic warfare, and other available weapons. *Techniques for Combined Arms for Air Defense*, Field Manual ATP 3-01.8 (Washington, D.C.: Headquarters, Department of the Army, July 2016), pp. 3.1–4.7.
49. Stanley J. Dougherty, *Defense Suppression: Building Some Operational Concepts* (Maxwell Air Force Base, Ala.: Air University Press, 1992), p. 7.
50. Radar provides all-weather, night-and-day, long-range detection, identification, and tracking.

the radar is switched off because airborne sensors can capture their radio communications and their thermal, radar, or visual signatures (produced by power-generation, radar reflections, or poor camouflage).[51] Here, the complexity of the surrounding terrain becomes central, as some environments such as the desert provide much less opportunity for concealment than cities or forests.[52]

Finally, the technology needs are greater for air defense than for land warfare.[53] Whereas well-trained soldiers armed with only automatic guns and explosives can pose a serious threat to highly mechanized land forces,[54] air defense requires advanced technologies for detecting, locating, identifying, tracking, and engaging enemy aerial intruders—such as early-warning and target acquisition radars, as well as antiaircraft guns and surface-to-air missiles.[55]

HIDER-FINDER COMPETITION FOR AIR DEFENSE. The challenges of air defense exceed these independent difficulties. Detecting incoming targets while avoiding detection also depends on the skills and capabilities of the adversary: the infrastructural, organizational, and technological capabilities of the enemy, as well as the proficiency of its personnel. To accomplish its goal, air defense requires specific tactics, procedures, techniques, technologies, operational planning, and supporting assets and capabilities to successfully intercept intruders, while simultaneously preventing the enemy from detecting, degrading, and destroying its own assets.

Air defense against a state that possesses only low-performing aircraft and lacks any supporting assets requires comparatively limited effort, skills, and capabilities (e.g., early-warning radar, command and communications centers, and relatively unsophisticated air defense systems). As the performances of enemy aircraft and supporting assets increase, however, the challenges of air defense become increasingly daunting, especially given the enemy's attempt to use decoys, electronic warfare, cyberattacks, and suppression of enemy air defenses assets in order to degrade and destroy the integrated air defense system or its individual units.[56]

But its electromagnetic signals can be detected by enemy radar warning receivers and antiradiation missiles.

51. *Techniques for Combined Arms for Air Defense*, pp. 3.1–3.6.

52. Cordesman and Wagner, *The Lessons of Modern War: Volume I*, p. 38.

53. *Electronic Warfare Fundamentals*, pp. 1.1–1.10.

54. Stephen D. Biddle, *Afghanistan and the Future of Warfare: Implications for Army and Defense Policy* (Carlisle, Pa.: Strategic Studies Institute, U.S. Army War College Press, 2002).

55. Barry R. Posen, "The War for Kosovo: Serbia's Political-Military Strategy," *International Security*, Vol. 24, No. 4 (Spring 2000), pp. 39–84, https://doi.org/10.1162/016228800560309.

56. In addition to disabling or destroying air defense outposts, suppression of enemy air defense assets can also have a psychological effect by forcing ground-based radars to either remain silent

Against capable enemies, an effective air defense requires an integrated network of multiple airborne and ground-based sensors and shooting platforms that complement one another.[57] This integrated network must possess sensors that provide long-range detection, which increases the reaction time for other systems to acquire and engage incoming targets. Generally, these sensors include strategically placed early-warning radars that are unreachable by an enemy's suppression or electronic warfare assets (i.e., deep inside one's territory or in safe heavens).[58] Air defense also requires a secure and reliable communications system that can rapidly transmit information to command and control centers for processing, and then to multiple engagement outposts so that the latter can acquire, track, and engage the intended target.[59] Moreover, a state must possess multiple types of engagement systems that are capable of intercepting both short-range/low-altitude and long-range/high-altitude incoming enemy aircraft.[60]

An enemy's efforts to find and degrade key nodes of the air defense systems and to avoid detection make the tasks of air defense even more challenging. The enemy will employ: a mix of cyberattacks to interfere with either the whole defense network or part of it, decoys and spoofing to deceive radars, jamming to degrade radars and communications, specific tactics such as flying at very low altitude to delay or reduce the chance of detection, and suppres-

or operate only intermittently (i.e., virtual attrition). Brungess, *Setting the Context*, p. 6; Eliot A. Cohen, *Gulf War Air Power Survey: Volume 4: Weapons, Tactics, and Training and Space Operations* (Washington, D.C.: Office of the Secretary of the Air Force, 1993), p. 94; and Benjamin S. Lambeth, *The Transformation of American Air Power* (Ithaca, N.Y.: Cornell University Press, 2000), p. 112.

57. By combining information provided by different sensors and systems, integrated air defense systems can detect a broader spectrum of targets than localized air defense systems. "The Cooperative Engagement Capability," *Johns Hopkins APL Technology Digest*, Vol. 16, No. 4 (1995), pp. 377–396, https://www.jhuapl.edu/Content/techdigest/pdf/V16-N04/16-04-APLteam.pdf; and Peter W. Mattes, "Systems of Systems: What, Exactly, Is an Integrated Air Defense System?" *Mitchell Forum*, No. 26 (Arlington, Va.: Mitchell Institute for Aerospace Studies, 2019).

58. Both North Vietnam during the Vietnam War and Yugoslavia during the Kosovo war deployed early-warning radars in areas that the United States could not strike for political or diplomatic reasons (i.e., north of the 20th parallel and in Montenegro). Yugoslavia also had "spotters" outside Italy's Aviano Air Base, from where many U.S. aircraft were taking off, that served as early-warning systems. See Nordeen, *Air Warfare in the Missile Age*, p. 28; and Benjamin S. Lambeth, "Kosovo and the Continuing SEAD Challenge," *Aerospace Power Journal*, Vol. 16, No. 2 (Summer 2002), p. 13, https://www.airuniversity.af.edu/Portals/10/ASPJ/journals/Volume-16_Issue-1-4/sum02.pdf.

59. Mattes, "Systems of Systems."

60. Surface-to-air missiles' long-range, high-altitude engagement capabilities make it difficult for aircraft that lack either active (e.g., jamming) or passive (e.g., low observability) countermeasures to penetrate enemy air defenses at high altitude. But "clutter interference" prevents surface-to-air missiles from engaging targets below a minimum altitude (generally about 1 kilometer). Short-range low-altitude air defense systems provide defense against low-flying targets. David Lynch Jr., *Introduction to RF Stealth* (Raleigh, N.C.: SciTech, 2004), pp. 195–221.

sion assets to destroy radars or to force them to limit emissions and/or to relocate.[61] Accordingly, states need to shield both their integrated air defense networks and their individual units from cyber, electronic, and physical (kinetic) attacks.[62] To this end, engagement outposts need radars with advanced electronic counter-countermeasures such as frequency-hopping and low-probability-of-intercept capabilities "to see without being seen."[63] But for electronic counter-countermeasures to be effective, they need to be more advanced than the enemy's electronic countermeasures, which entails taking part in a never-ending technological race.[64] The same is true for cyber defense.[65] Moreover, the air defense network needs advanced ground-based and airborne radar systems that can also detect small targets flying at low altitude.[66] Such detection capability requires these radar systems to automatically and effectively filter out unwanted radar returns, match the radar returns of potential interest with an existing stock of radar signatures, or exploit the intruders' other features (e.g., their Identification Friend or Foe [IFF] transponder) to increase the probability of detecting an intruder and of correctly distinguishing it from decoys or clutter.[67] Finally, air defense also requires highly skilled per-

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61. Because of the earth's curvature, radar beams will not be able to illuminate objects that fly below a given altitude—an area called "radar shadow." Bronk, "Modern Russian and Chinese Integrated Air Defence Systems," p. 10.
62. In the 1999 Kosovo War, the United States used information warfare through cyber infiltration and cyberattacks with the goal of deceiving Yugoslavia's radars and integrated air defense system. Benjamin S. Lambeth, *NATO's Air War for Kosovo: A Strategic and Operational Assessment* (Santa Monica, Calif.: RAND, 2001), p. 112. For more recent cyberattacks to air defense systems, see Shane Quinlan, "Jam. Bomb. Hack? New U.S. Cyber Capabilities and the Suppression of Enemy Air Defenses," *Georgetown Security Studies Review*, published online April 7, 2014, https://georgetownsecuritystudiesreview.org/2014/04/07/jam-bomb-hack-new-u-s-cyber-capabilities-and-the-suppression-of-enemy-air-defenses/.
63. Philip E. Pace, *Detecting and Classifying Low Probability of Intercept Radar*, 2nd ed. (Norwood, Mass.: Artech, 2009), p. 48. On frequency hopping and low-probability intercept, see, respectively, Simon Kingsley and Shaun Quegan, *Understanding Radar Systems* (Norwich, N.Y.: SciTech, 1999), pp. 286–295; and Pace, *Detecting and Classifying Low Probability of Intercept Radar*, pp. 1–40, 187–205. Counter-countermeasures also include active and passive radar decoys aimed at confusing or deceiving anti-radiation missiles. See Filippo Neri, *Introduction to Electronic Defense Systems* (London: Artech, 2018), pp. 535–536.
64. Alfred Price, *War in the Fourth Dimension: U.S. Electronic Warfare, from the Vietnam War to the Present* (London: Greenhill, 2001); and Alfonso Farina, "Electronic Counter-Countermeasures," in Merrill I. Skolnik, ed., *Radar Handbook* (New York: McGraw-Hill, 2008), pp. 24.1–24.58.
65. Max Smeets, "Cyber Arms Transfer: Meaning, Limits, and Implications," *Security Studies*, published online February 2022, https://doi.org/10.1080/09636412.2022.2041081.
66. Airborne "look-down" radars address the threat of low-flying targets. George W. Stimson, *Introduction to Airborne Radar*, 2nd ed. (Mendham, N.J.: SciTech, 1998), pp. 23–24, 40–45; and William W. Shrader and Vilhelm Gregers-Hansen, "MTI Radar," in Merrill Skolnik, ed., *Radar Handbook*, 3rd ed. (New York: McGrawHill, 2008), pp. 2.1–2.91.
67. Advanced signal processing and a large stock of environmental data will lower the probability of false alarms and hence increase the probability of detection. Lynch, *Introduction to RF Stealth*,

sonnel, as well as appropriate concepts of operations.[68] Maintaining radio silence, enforcing emission control, and relocating mobile air defense systems is burdensome, dangerous, and difficult.[69] If they are detected by enemy platforms, mobile air defense system operators must rapidly relocate, taking advantage of terrain to conceal their movements and their new positions.[70]

THE MODERN SYSTEM FOR AIR PENETRATION

Modern air defense systems represent a lethal threat for military aircraft. Accordingly, military aircraft have to avoid, degrade, or destroy ground-based air defense systems in order to penetrate the enemy's air space and carry out the intended mission.[71] Avoiding detection while searching for enemy's targets inside the adversary's territory is very challenging, for two sets of factors.

THE CHALLENGE OF AIR PENETRATION. The modern system of force employment is even more daunting for penetrating aircraft than for air defense. Critically, the air domain does not offer opportunities for cover from enemy fire.[72] Because aircraft can tolerate little structural damage, they need to avoid detection altogether.[73] Moreover, in contrast to the land domain, the air do-

pp. 209–221; and William G. Ballard and Stéphane Kemkemian, "Fire-Control Radar," in William L. Melvin and James A. Scheer, eds., *Principles of Modern Radar: Vol. 3: Radar Applications* (Edison, N.J.: SciTech, 2014), pp. 117–174. A stock of an enemy's radar signatures will lower the probability of missed detections, especially against targets with small radar cross sections. Kristin F. Bing, Lisa M. Ehrman, and Teresa M. Selee, "Automatic Target Recognition," in William L. Melvin and James A. Scheer, eds., *Principles of Modern Radar: Vol. 2: Advanced Techniques* (Edison, N.J.: SciTech Publishing, 2013), pp. 631–668. See also Oleg I. Sukharevsky, ed., *Electromagnetic Wave Scattering by Aerial and Ground Radar Objects* (Boca Raton, Fla.: CRC, 2014), pp. xix, 91. In the late 1960s, the United States fielded the QRC-248 enemy IFF transponder interrogator that could identify Soviet fighter jets among countless radar returns by using their aircraft's own systems of identification. Marshall L. Michel III, *Clashes: Air Combat over North Vietnam, 1965–1972* (Annapolis, Md.: Naval Institute Press, 1997), pp. 100–101. In the 1970s, the U.S. Air Force made significant advances in signal processing. A high-resolution radar system could count the number of blades in the engine of the aircraft under surveillance. By matching the number of blades to an existing stock of data, long-range identification became possible. Kenneth P. Werrell, *Chasing the Silver Bullet: U.S. Air Force Weapons Development from Vietnam to Desert Storm* (Washington, D.C.: Smithsonian Institution Scholarly Press, 2003), p. 71.

68. Bruce R. Orvis, Michael Childress, and J. Michael Polich, *Effect of Personnel Quality on the Performance of Patriot Air Defense System Operators* (Santa Monica, Calif.: RAND, 1992).
69. Tirpak, "Dealing with Air Defense."
70. *Techniques for Combined Arms for Air Defense*, pp. 3.1–3.15.
71. Heilenday, *Principles of Air Defense and Air Vehicle Penetration*, pp. 2.1–2.6.
72. Rotary-wing aircraft are an exception because they can move vertically to take advantage of natural or artificial obstacles for cover from enemy fire. Fixed-wing aircraft can also take advantage of natural and artificial obstacles, but mostly for concealment rather than for cover. See *Techniques for Combined Arms for Air Defense*, pp. 1.6–1.7.
73. John Stillion and Bryan Clark, *What It Takes to Win: Succeeding in 21st Century Battle Network Competitions* (Washington, D.C.: CSBA, 2015), p. 48.

main offers only limited opportunities for concealment.[74] To radar systems, aircraft appear significantly different from the background in which they operate, the sky.[75] As a result, penetrating aircraft are generally easier to detect and target than land-based air defense systems because of the differences between their surrounding environments—simple for aircraft and complex for ground-based systems.[76] Finally, air penetration is heavily dependent on technologies that reduce an aircraft's exposure to enemy firepower, both for limiting detection and for avoiding interception once detected.[77]

HIDER-FINDER COMPETITION FOR AIR PENETRATION. In addition to these independent constraints, the challenge of air penetration is a function of an enemy's air defenses: the capabilities and sophistication of the available technologies and assets as well as the proficiency of personnel operating them. To penetrate the air space of a country that possesses limited air defenses, such as antiaircraft guns and man-portable air defense systems, an air force will need to fly just beyond their maximum altitude reach.[78] In this scenario, air penetration still requires significant infrastructural support in terms of intelligence gathering and processing, target acquisition, and mission planning, as well as communications.[79] But degrading and destroying enemy air defenses might not even be necessary.[80]

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74. There are opportunities for concealment in the air domain, such as taking advantage of the "radar shadow" discussed previously, or of the super-refracting duct that forms, under certain conditions, over large bodies of water and that shields aircraft flying above a given altitude from radar detection. *Electronic Warfare Fundamentals*, pp. 2.9–2.14.
75. "Significantly" is intended in statistical terms. Detection is a probabilistic assessment that relies on inferential statistics to distinguish an object from its background with the goal of minimizing the risk of a false alarm and of a miss. Mark Denny, *Blip, Ping, and Buzz: Making Sense of Radar and Sonar* (Baltimore, Md.: Johns Hopkins University Press, 2008), pp. 46–89; and J. C. Toomay and Paul J. Hannen, *Radar Principles for the Non-specialist*, 3rd ed. (Raleigh, N.C.: SciTech, 2004), pp. 1–44.
76. Stephen Biddle and Ivan Oelrich, "Future Warfare in the Western Pacific: Chinese Antiaccess/Area Denial, U.S. AirSea Battle, and Command of the Commons in East Asia," *International Security*, Vol. 41, No. 1. (Summer 2016), pp. 12–13, https://doi.org/10.1162/ISEC_a_00249.
77. Detection can be avoided in different ways, most prominently by reducing the radar signature of an aircraft (stealth technology). See William F. Bahret, "The Beginnings of Stealth Technology," *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 29, No. 4 (October 1993), pp. 1377–1385, https://doi.org/10.1109/7.259548. Interception can be avoided by outmaneuvering an incoming missile (which depends on the maneuverability of an aircraft) or by using passive systems such as chaff or flares that deceive radar-guided and heat-seeking missiles, respectively. See *Electronic Warfare Fundamentals*, pp. 13.1–13.16, 15.1–15.8.
78. Typically, the altitude ceiling and maximum range for antiaircraft guns are 6 kilometers and 10 kilometers, respectively, and 3.5 kilometers and 8 kilometers for man-portable air defense systems.
79. Mark Gunzinger et al., *An Air Force for an Era of Great Power Competition* (Washington, D.C.: CSBA, 2019), pp. 13–14.
80. Joshi and Stein, "Emerging Drone Nations"; and Gilli and Gilli, "The Diffusion of Drone Warfare?"

Air penetration becomes more demanding as the enemy deploys more advanced air defense systems.[81] Against a state that possesses an integrated air defense system capable of detecting, tracking, and engaging both long-range high-altitude and short-range low-altitude targets, air penetration requires specific tactics, proved procedures, extensive operational planning, supporting assets, advanced technology, as well as experienced and proficient personnel.[82] To penetrate and operate in highly contested air spaces, a state needs aircraft specifically designed for the mission (i.e., stealth), which in turn calls for an advanced industrial, scientific, and technological base.[83] Stealth aircraft, however, are necessary but insufficient against advanced air defense systems.[84] A state will also have to employ a mix of cyberattacks, electronic warfare, and suppression assets to lower the risk of interception for its stealth aircraft. But each of these options entails significant infrastructural, organizational, and technological capabilities, and their success is a function of the relative capabilities of the two fighting sides.[85]

Specifically, intelligence, surveillance, and reconnaissance (ISR) platforms must detect and locate an enemy's air defense outposts and share the latter's exact coordinates in a timely manner with mission planners. In this way, mission planners can identify path profiles that minimize the risk for penetrating aircraft, by either exploiting existing gaps in radar coverage or creating them through suppression of enemy air defense systems and electronic warfare assets that target and degrade critical nodes in the enemy's network.[86]

81. Air defense forces enemy intruders to change their behavior, otherwise they would experience significant attrition (such a change of behavior is called virtual attrition). For instance, the threat of surface-to-air missiles during the Vietnam War forced U.S. aircraft to fly below a given altitude, which in turn exposed them to antiaircraft guns. Werrell, *Archie to SAM*, pp. 138.

82. *Electronic Warfare Fundamentals*, pp. 17.15–17.20; and Mattes, "Systems of Systems."

83. For a discussion of the challenges of developing stealth fighter jets, see Andrea Gilli and Mauro Gilli, "Why China Has Not Caught Up Yet: Military-Technological Superiority and the Limits of Imitation, Reverse Engineering, and Cyber Espionage," *International Security*, Vol. 43, No. 3 (Winter 2018/19), pp. 141–189, https://doi.org/10.1162/isec_a_00337.

84. Kopp, "Evolving Technological Strategy in Advanced Air Defense Systems," pp. 89–92.

85. Jon R. Lindsay, "Stuxnet and the Limits of Cyber Warfare," *Security Studies*, Vol. 22, No. 3 (2013), pp. 365–404, https://doi.org/10.1080/09636412.2013.816122; Rebecca Slayton, "What Is the Cyber Offense-Defense Balance? Conceptions, Causes, and Assessment," *International Security*, Vol. 41, No. 3 (Winter 2016/17), pp. 72–109, https://doi.org/10.1162/ISEC_a_00267; and Lennart Maschmeyer, "The Subversive Trilemma: Why Cyber Operations Fall Short of Expectations," *International Security*, Vol. 46, No. 2 (2021), pp. 51–90, https://doi.org/10.1162/isec_a_00418.

86. These tasks entail collecting and rapidly processing data from different types of intelligence (e.g., signal, electronic, photographic, human, and operational). Against a technologically deficient or non-proficient enemy, these tasks will be easier to carry out because the enemy might fail to hide and conceal its air defenses. Against more capable enemies, these tasks will become more difficult. For a discussion of this aspect in the 1982 Lebanon War, see Benjamin S. Lambeth, *Moscow's Lessons from the 1982 Lebanon Air War* (Santa Monica, Calif.: RAND, 1984), pp. 4–8; David E.

These personnel must carry out their individual tasks in strict and time-sensitive sequence with limited margins for error to maximize surprise and impact.[87]

Such tasks are even more difficult because of the enemy's attempt to conceal key assets, create false targets (e.g., radio frequency emitters and weapon systems mock-ups), and employ countermeasures, which aim at maintaining active ground-based air defenses.[88] To address the threat posed by concealed, mobile, or surviving air defense systems, military personnel should employ decoys to deceive an enemy's air defense systems into activating their acquisition radars and thus revealing their positions, which allows suppression assets to detect and target them.[89] Additionally, electronic warfare platforms must be in the position to effectively degrade (i.e., "blind" or "deceive") remaining enemy radars to minimize the threats to the strike aircraft.[90] The aircraft must then proceed through temporary corridors created by the degraded or destroyed enemy air defense systems while taking advantage of natural and artificial obstacles such as mountains or buildings.[91] Given the lethality of modern air defense systems,

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Clary, "Bekaa Valley—A Case Study," Student Report, Air Command and Staff College, Air University, Maxwell Air Force Base, Alabama, 1988, pp. 9–11; and Rebecca Grant, "The Bekaa Valley War," *Air Force Magazine*, June 1, 2002, https://www.airforcemag.com/article/0602bekaa/.

87. For an empirical summary of a successful air penetration campaign against a country possessing advanced air defense, see Eliot A. Cohen, *Gulf War Air Power Survey: Vol. 2: Operations and Effects and Effectiveness* (Washington, D.C.: Office of the Secretary of the Air Force, 1993), pp. 115–158.

88. Posen, "The War for Kosovo," pp. 54–58; and Rip and Hasik, *The Precision Revolution*, pp. 401–406.

89. To deceive enemy radars, decoys need to have radar returns similar to those of attacking aircraft, which require specific technological capabilities. David Clary, "EW in the Bekaa Valley: A New Look," *Journal of Electronic Defense*, (June 1990), p. 38; and Tirpak, "Dealing with Air Defense," p. 28. Similarly, antiradiation missiles and loitering munitions need to possess high-speed and long loitering time capabilities so that they can target radar outposts. During the 1999 Kosovo War, for instance, neutralizing Yugoslavia's integrated air defense system was, according to the commander of NATO forces, "like digging out potatoes one at a time." Dana Priest, "NATO Pilots Set to Confront Most Powerful Foe Since Iraq," *Washington Post*, March 24, 1999, https://www.washingtonpost.com/archive/politics/1999/03/24/nato-pilots-set-to-confront-most-powerful-foe-since-iraq/4905d3f1-7627-4055-a235-acbe4957c75a/.

90. During the Gulf War, the F-117 Nighthawk stealth aircraft did not require the support of electronic warfare assets because its small radar signature significantly reduced the range of detection by enemy radars, thus allowing it to penetrate Iraqi's air defense systems. But advances in radar systems have largely eroded such an advantage, which is why newer stealth aircraft such as the F-35 Joint Strike Fighter Lightening II possess their own electronic warfare suits. Cohen, *Gulf War Air Power Survey: Vol. 2*, p. 123; Loren Thompson "The F-35 Isn't Just 'Stealthy': Here's How Its Electronic Warfare System Gives It an Edge," *Forbes*, May 13, 2019, https://www.forbes.com/sites/lorenthompson/2019/05/13/how-a-super-agile-electronic-warfare-system-makes-f-35-the-most-invincible-combat-aircraft-ever/; and Kopp, "Evolving Technological Strategy in Advanced Air Defense Systems," pp. 89–92.

91. On how mission planning, decoys, and electronic warfare can increase aircraft survivability in a contested airspace, see *Electronic Warfare Fundamentals*, pp. 9.1–13.16; Lynch, *Introduction to RF*

these considerations apply to any aircraft, stealth included.[92] Finally, penetrating aircraft require reliable and secure communications.[93]

Research Design

In this section, we derive the observable implications of both the drone revolution thesis and the modern system of force employment in air warfare for three dependent variables: offense-defense balance, distribution of power, and force employment. Then, we explain the rationale behind our case selection.

OFFENSE-DEFENSE BALANCE: THE OFFENSIVE ADVANTAGE OF DRONES?

Scholars have argued that drones yield an offensive advantage because they can penetrate an enemy's air defense systems. According to some, because of their small size and other physical features, drones are difficult to detect, track, and intercept for modern air defense systems. According to others, the cheap cost of drones makes them expendable and would allow countries to employ them to numerically overwhelm an enemy's air defense system (saturation). If the drone revolution thesis were correct, we should observe at least one of the following three outcomes: (1) drones should experience little attrition when penetrating enemy air spaces; (2) drones should be able to carry out air-to-ground attacks over enemy territories protected by air defense systems; or (3) drones should be able to systematically destroy enemy air defenses. Given that current-generation drones are vulnerable to air defense systems, according to our framework, we expect that the attrition rate drones experience and hence their success in carrying out air-to-ground attacks is a function of the relative skill, proficiency, and capabilities of the sides in conflict (i.e., hiding from the enemy's sensors while finding the enemy's targets).[94]

Stealth, pp. 221–262; and Rebecca Grant, *The Radar Game: Understanding Stealth and Aircraft Survivability* (Arlington, Va.: Mitchell Institute for Aerospace Studies, September 2010), pp. 36–53.

92. As the shooting down of the F-117 Nighthawk in Yugoslavia shows, even stealth aircraft need to know the exact locations of enemy air defenses because it permits them to identify a path profile that further minimizes the risk of detection. Cohen, *Gulf War Air Power Survey: Vol. 4*, pp. 243–244; and Myron Hura and Gary McLeod, *Route Planning Issues for Low Observable Aircraft and Cruise Missiles: Implications for the Intelligence Community* (Santa Monica, Calif.: RAND, 1993). In fact, insufficient attention to mission planning contributed to the shooting down of the F-117 in Yugoslavia. Lambeth, "Kosovo and the Continuing SEAD Challenge," pp. 12–14.

93. Mark Gunzinger and Bryan Clark, *Sustaining America's Precision Strike Advantage* (Washington, D.C.: CSBA, 2015), p. 26.

94. We study the offense advantage in dyadic terms. See Keir A. Lieber, *War and the Engineers: The Primacy of Politics on Technology* (Ithaca, N.Y.: Cornell University Press, 2005), pp. 149–158. On

DISTRIBUTION OF POWER: THE LEVELING EFFECT OF DRONES?

Proponents of the drone revolution thesis suggest that, since UAVs are easy to produce, cheap to procure, and simple to use, drones strengthen militarily weaker and resource-scarce actors and thereby exert a leveling effect on international politics. If this thesis were correct, across conflicts, weaker actors should be more likely to rely on drones (in either absolute terms or relative to its other weapon systems), especially when facing significantly stronger adversaries, or when military defeat nears.[95] Conversely, we expect that using drones effectively requires additional assets for blinding and deceiving enemy radars, suppressing air defenses, detecting and acquiring long-range targets, and transmitting and receiving real-time communications (especially when line of sight is unavailable). Consequently, the stronger actor in a conflict will be more likely to employ drones.

FORCE EMPLOYMENT: OBSOLESCENCE OF CLOSE COMBAT?

Finally, some drone revolution proponents believe that drones permit unrestrained long-range precision strikes that can destroy, at will, any intended target. As a result, using drones should make ground combat unnecessary, and it should make the factors that affect performance in land warfare less relevant (e.g., the proficiency of military personnel). According to our theory, close combat will not disappear because ground forces will continue to have opportunities for concealment, especially in urban settings.

CASE SELECTION

We test the observable implications of the drone revolution in military affairs and of the modern system of force employment in three recent conflicts: the Western Libya military campaign, the Syrian civil war, and the Armenia-Azerbaijan conflict over Nagorno-Karabakh. UAVs have been used extensively in these conflicts, which some have hailed as paragons of the revolutionary effects that drones exert on the battlefield.[96] As Jason Lyall writes, "The world

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the vulnerability of current-generation drones, see Antonio Calcara et al., "Will the Drone Always Get Through? Emerging Technologies and the Cult of the Offensive," working paper, ETH-Zürich, Zurich, 2022.

95. This logic has driven the adoption of other inexpensive but effective military innovations such as suicide attacks. See Andrea Gilli and Mauro Gilli, "The Spread of Military Innovations: Adoption Capacity Theory, Tactical Incentives and the Case of Suicide Terrorism," *Security Studies*, Vol. 23, No. 3 (Summer 2014), pp. 513–547, https://doi.org/10.1080/09636412.2014.935233.

96. Tom Kington, "Libya is Turning into a Battle Lab for Air Warfare," *Defense News*, August 6, 2020, https://www.defensenews.com/smr/nato-air-power/2020/08/06/libya-is-turning-into-a-battle-lab-for-air-warfare/; Mariya Petkova, "Turkish Drones—A 'Game Changer' in Idlib," *Al Jazeera*, March 2, 2020, https://www.aljazeera.com/news/2020/3/2/turkish-drones-a-game-changer-in; and Hambling, "The 'Magic Bullet.'"

has entered an era of drone wars. In four major interstate wars . . .—those in Libya, Nagorno-Karabakh, Syria, and Ukraine—armed drones played a dominant, perhaps decisive, role."[97] A priori, these cases should then be particularly favorable for the drone revolution thesis, and unfavorable for our argument. Moreover, these conflicts feature significant within-case and cross-case variation, which permits us to address several confounders. The war in Libya was fought between two comparably weak actors, the Government of National Accord (GNA) and the Libyan National Army (LNA). Yet the external support they received varied over time. Specifically, the LNA enjoyed significantly stronger initial support, while the GNA received more support in later stages of the conflict. Similarly, the intervention of foreign states skewed the tactical and operational balance in Syria (i.e., Iran and Russia provided support to the Syrian regime, the United States supported the Syrian opposition, and Turkey fought against Kurdish groups). Finally, in Nagorno-Karabakh, Azerbaijan possessed superior capabilities compared with Armenia, it benefited from Turkey's ISR and electronic warfare assets, and it relied on special forces for behind-enemy-lines infiltrations and on mercenaries for ground operations.

Our empirical analysis relies on information from news outlets, published reports, and open-source operational assessments. For recent conflicts, such sources are inherently problematic because some information might be inaccurate, embellished, biased, or fraudulent. These issues affect the study of war in general, and even more so recent conflicts in which independent academics and analysts have not had the opportunity to assess and validate multiple sources.[98] To compensate for this limitation, we analyze and triangulate several primary and secondary sources for each claim, to minimize the risk of relying on inaccurate information.[99] Although we doubt that new evidence will challenge our conclusions, this cautionary warning is still necessary.

The Drone War in Libya, 2019–2020

In 2011, NATO military operation Odyssey Dawn/Unified Protector ended Muammar Qaddafi's forty-two-year rule over Libya.[100] A civil war soon en-

97. Jason Lyall, "Drones Are Destabilizing Global Politics," *Foreign Affairs*, December 16, 2020, https://www.foreignaffairs.com/articles/middle-east/2020-12-16/drones-are-destabilizing-global-politics.
98. Stathis N. Kalyvas, *The Logic of Violence in Civil War* (Cambridge: Cambridge University Press, 2006), p. 35.
99. See the online appendix for additional source material.
100. Christopher S. Chivvis, *Toppling Qaddafi: Libya and the Limits of Liberal Intervention* (Cambridge: Cambridge University Press, 2013).

sued among multiple factions, tribes, mercenaries, and the Islamic State (ISIS).[101] In 2015, two main actors emerged: the GNA, which was based in Tripoli and led by Fayez al-Sarraj, with control of the state's western coastal area, recognized by the United Nations and backed by Turkey; and the LNA, which was based in Tobruk and led by General Khalifa Haftar, with control of the eastern coastal and continental area, and supported by Russia, the United Arab Emirates (UAE), and Egypt.[102] In this section, we analyze the extensive use of drones in the 2019–2020 Western Libya military campaign, in which the GNA and the LNA fought for the control of Tripoli and of the western coastal part of Libya (Tripolitania).[103] From April to November 2019, there were over 1,040 recorded drone strikes during this military campaign, prompting Ghassan Salamé, Special Representative of the Secretary-General and Head of the United Nations Support Mission in Libya, to speak of "the largest drone war in the world."[104] The Western Libya military campaign thus represents an ideal case to test the drone revolution thesis. Moreover, some drone revolution proponents have suggested that the use of drones in this conflict was a "game changer," which has implications for the "future of warfare."[105] Our analysis does not support this interpretation. Drones did not yield an offensive advantage, they did not strengthen the militarily weaker side, and they did not eliminate the need for close combat and ground operations.

offensive advantage

In the Western Libya military campaign, drones failed to penetrate enemy air defense systems and thus yielded no offensive advantage against capable enemies. Far from operating "with impunity," as the drone revolution thesis suggests, drones suffered "a relatively high rate of attrition from ground-fired

101. Christopher S. Chivvis and Jeffrey Martini, *Libya after Qaddafi: Lessons and Implications for the Future* (Santa Monica, Calif.: RAND, 2014).
102. Wolfram Lacher, *Libya's Fragmentation: Structure and Process in Violent Conflict* (London: Bloomsbury, 2020).
103. Whereas the 2011 war was probably "the first real drone war," there is no evidence that drones were used in this conflict between 2015 and 2018. Spencer Ackerman, "Libya: The *Real* U.S. Drone War," *Wired*, October 20, 2011, p. 217, https://www.wired.com/2011/10/predator-libya/; and Gettinger, *The Drone Databook*.
104. UN Meetings Coverage, "Foreign Involvement in Libya Must Be Stopped, Top Official Tells Security Council, Describing 'Race against Time' to Reach Peaceful Solution, Spare Lives," UN Security Council Meeting No. 8667, November 18, 2019 (New York: United Nations, 2019), https://www.un.org/press/en/2019/sc14023.doc.htm; and "Interview with UN Special Representative for Libya Ghassan Salamé," September 25, 2019, United Nations Political and Peacebuilding Affairs, YouTube video, https://www.youtube.com/watch?v=IB3jie4i7SI.
105. Kington, "Libya Is Turning into a Battle Lab for Air Warfare"; and Nathan Vest and Colin P. Clarke, "Is the Conflict in Libya a Preview of the Future of Warfare?" *Defense One*, June 2, 2020, https://www.defenseone.com/ideas/2020/06/conflict-libya-preview-future-warfare/165807/.

missiles."[106] Between early 2019 and mid-2020, the GNA lost twenty-two of its twenty-four drones in operations.[107] Similarly, LNA lost between one-third and one-half of the drones it is estimated to have possessed.[108] Second, attrition rates among combat drones correlate with the presence and capabilities of the adversaries' air defense systems. In the initial phase of the conflict, the LNA had access to Russian short-range air defense systems (Pantsir S-1) supplied by the UAE. As a result, the GNA's drones were decimated, bringing their operations to a halt.[109] In contrast, the GNA had only inferior antiaircraft guns and man-portable air defense systems, which could shoot down some of the LNA's drones but could not stop the whole campaign.[110] The tide turned in November 2019, however, when Turkey deployed in the airports of Misrata and Mitiga two HAWK II surface-to-air batteries and its KORAL advanced electronic warfare systems in support of the GNA.[111] The former enabled the GNA to repeatedly shoot down the LNA's drones, while the latter blinded LNA's air defenses, thus allowing the GNA to resume drone operations and strikes.[112]

LEVELING EFFECT

Throughout the Western Libya military campaign, drones did not strengthen the militarily weaker side. Instead, UAVs exacerbated existing battlefield

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106. Franz-Stefan Gady, "Useful, but Not Decisive: UAVs in Libya's Civil War," International Institute for Strategic Studies, November 22, 2019, https://www.iiss.org/blogs/analysis/2019/11/mide-uavs-in-libyas-civil-war. See also Aaron Stein, "Say Hello to Turkey's Little Friend: How Drones Help Level the Playing Field," *War on the Rocks*, June 11, 2021, https://warontherocks.com/2021/06/say-hello-to-turkeys-little-friend-how-drones-help-level-the-playing-field/.
107. Jason Pack and Wolfgang Pusztai, "Turning the Tide: How Turkey Won the War for Tripoli" (Washington, D.C.: Middle East Institute, November 2020), p. 5, https://www.mei.edu/sites/default/files/2020-11/Turning%20the%20Tide%20-%20How%20Turkey%20Won%20the%20War%20for%20Tripoli.pdf; and Chris Cole and Jonathan Cole, "Libyan War Sees Record Number of Drones Brought Down to Earth," *Drone Wars*, July 1, 2020, https://dronewars.net/2020/07/01/libyan-war-sees-record-number-of-drones-brought-down-to-earth/.
108. According to analysts, "up to six Bayraktar [of the GNA] and at least one Wing Loong [of the LNA] have been lost" during 2019; in the first half of 2020, sixteen TB2s operated by the GNA and eight Wing Loongs operated by the LNA either crashed or were intercepted. Data are from Drone Crash Database (Oxford: Drone Wars UK, 2022), https://dronewars.net/drone-crash-database/; and Gady, "Useful, but Not Decisive."
109. Pack and Pusztai, "Turning the Tide," p. 5; and Paul Iddon, "Turkey Is Fighting a Formidable Drone War in Libya," *Ahval*, September 14, 2019, https://ahvalnews.com/libya/turkey-fighting-formidable-drone-war-libya.
110. Pack and Pusztai, "Turning the Tide," p. 5.
111. Feridun Taşdan, "Turkish EW Systems: The Unseen Force behind Recent Turkish Drone Successes," *Defense Turkey*, May 2021, https://www.defenceturkey.com/en/content/turkish-ew-systems-the-unseen-force-behind-recent-turkish-drone-successes-4532; and Ali Bakir, "Turkey's Electronic Warfare Capabilities: The Invisible Power behind Its UACVs," *RUSI*, September 27, 2021, https://rusi.org/explore-our-research/publications/commentary/turkeys-electronic-warfare-capabilities-invisible-power-behind-its-uacvs.
112. Pack and Pusztai, "Turning the Tide," p. 5.

imbalances, an outcome that is consistent with the modern system of force employment in air warfare.

First, it was the stronger side—not the weaker one—that used drones more widely and with greater success.[113] The LNA inherited and seized a significant part of the military equipment of the Libyan government, and during the first part of the military campaign, in early 2019, it also received support from the UAE, Russia, and Egypt in terms of logistics, communications, drones, antiair defense systems, and other military equipment such as fighter jets (the LNA's fleet came to possess, among others, MiG-21s, MiG-23s, Mirage 2000s, F-16s, and, allegedly, Rafales).[114]

Second, drones did not help the weaker side, the GNA, overcome its tactical and strategic inferiority. Lacking complementary military capabilities and external support, the GNA was unable to even carry out drone strikes during the early phase of the Western Libya campaign. Some of its drones were shot down by the LNA's air defense systems, whereas others were destroyed while parked on runways.[115]

Third, the introduction of drones did not alter the balance of forces in the battlefield. Between May and July 2019, Turkey provided the GNA with twelve Bayraktar TB2 drones. But these drones did not allow the GNA to contest the LNA's air and military superiority. Instead, the LNA "virtually eradicated from the aerial battlefield" the GNA's newly acquired drones within a few months.[116] The tactical balance shifted when Turkey provided the GNA with air defense, electronic warfare systems, and proficient personnel, which addressed GNA's vulnerabilities and enabled its forces to offset the LNA's capabilities.[117] The GNA could then launch its own campaign of

113. The GNA had twelve to twenty-four drones compared with twenty to thirty for the LNA. Gady, "Useful, but Not Decisive"; and Pack and Pusztai, "Turning the Tide."
114. Garrett Reim, "Record Number of UAV Shoot Downs Prompt New USAF Tactics and Countermeasure Pod," *Flight Global*, June 30, 2020, https://www.flightglobal.com/military-uavs/record-number-of-uav-shoot-downs-prompt-new-usaf-tactics-and-countermeasure-pod/138908.article; and International Institute for Strategic Studies [IISS], *The Military Balance 2019* (London: Routledge, 2019), p. 356. In Libya, the UAE deployed at least six AT-802s, two UH-60Ms, and two Wing Loong I (GJ-1) UAVs in 2019. See IISS, *The Military Balance 2019*, p. 356; and "UAE Mirages Deployed in Egypt," *Itamilradar*, May 7, 2020, https://www.itamilradar.com/2020/05/07/uae-mirages-deployed-in-egypt/.
115. Iddon, "Turkey Is Fighting a Formidable Drone War in Libya."
116. Pack and Pusztai, "Turning the Tide," p. 5. See also Bayraktar TB2 UAS Technical Specifications, *Baykar Tech*, https://cdn.baykartech.com/media/upload/userFormUpload/sy7JH9hB9upCek920ObOU7SOc2ihH9gr.pdf; Iddon, "Turkey Is Fighting a Formidable Drone War in Libya"; and IISS, *The Military Balance 2019*, p. 356.
117. Many NATO states consider Turkish electronic warfare capabilities to be very advanced. Bakir, "Turkey's Electronic Warfare Capabilities."

drone strikes, which ultimately helped tilt the military balance and hence the course of the conflict.[118]

Fourth, we did not find any evidence suggesting that the weaker actor could quickly and cheaply produce or acquire military drones to either offset its combat losses or tactical inferiority, or to alter the operational imbalance. Additionally, all drones that were used during the conflict were made, supplied, and operated by foreigners.[119]

CLOSE COMBAT AND FORCE EMPLOYMENT

Finally, according to the drone revolution thesis, long-range precision drone strikes should cancel close combat, thereby making force employment less relevant. Our empirical investigation does not support this perspective.

First, close combat has not disappeared.[120] For instance, on April 4, 2020, the LNA attempted to retake Tripoli. Given the risk of urban warfare and its associated heavy civilian casualties, however, the LNA employed "a cat-and-mouse military maneuver that sought to draw the anti-LNA forces into the open or the outskirts of the city," where lack of buildings exposed targets to enemy weapons.[121] Besides artillery and airpower, throughout the Western Libya campaign both the LNA and the GNA relied on infantry units and mercenaries to take control of and defend strategic infrastructures such as airports, highways, and major intersections, to launch land offensives, to retake terrain, or to execute mop-up operations.[122] Starting in May 2019, the GNA's military leaders began to hire foreign fighters from Chad and Darfur. In December 2019, Turkey started to deploy mercenaries from Syria in order to support al-Sarraj's forces, which grew from about 1,000 in January 2020

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118. Ben Fishman and Conor Hiney, "What Turned the Battle for Tripoli?" *Policy Watch* 3314, Washington Institute for Near East Policy, May 6, 2020, https://www.washingtoninstitute.org/policy-analysis/view/what-turned-the-battle-for-tripoli.
119. UAE pilots stationed at the Al Khadim air base (south of Tripoli) operated the LNA's Chinese drones, while Turkish personnel operated its domestically produced drones from airfields in Misrata and Mitiga. Gady, "Useful, but Not Decisive"; and "Erdogan: Turkey Will Increase Military Support to GNA If Needed," *Al Jazeera*, December 22, 2019, https://www.aljazeera.com/news/2019/12/22/erdogan-turkey-will-increase-military-support-to-gna-if-needed. Other sources provide a similar count of Turkish attack drones (twenty), such as Thomas Harding, "Revealed: How Turkey Ramped Up Libyan Drone Attacks to Escalate Conflict," *National News*, July 21, 2020, https://www.thenationalnews.com/world/revealed-how-turkey-ramped-up-libyan-drone-attacks-to-escalate-conflict-1.1051869.
120. The Battle for Tripoli started as an attempt by the LNA to conquer the capital of Libya. As the LNA conquered territory surrounding the city, the battle became a siege. As the GNA regained momentum, the battle expanded to the rest of Tripolitalia.
121. Pack and Pusztai, "Turning the Tide," p. 3.
122. Ibid., p. 10.

to about 15,000 over the summer.[123] Likewise, the LNA hired troops from Libya's Toubou ethnic group as well as from Sudan and Chad to defend oil installations, fields, and airstrips.[124] In August 2020, the private military company Wagner Group provided the LNA with additional tactical assistance and ISR operations for artillery and aerial strikes.[125] Similarly, Turkey's support of the GNA (e.g., the deployment of surface-to-air missile batteries in the airports of Misrata and Mitiga, electronic warfare systems, and frigates for offshore detection) not only stopped the LNA's air superiority but also allowed the GNA's ground forces to counterattack, thus ending the siege of Tripoli and preventing the fall of the Libyan capital to the LNA.[126]

Second, combat proficiency in modern warfare has not lost relevance. For instance, Turkey's electronic warfare system helped GNA forces detect, locate, and target the LNA's air defense systems, which could then be engaged by drones. But the tactical balance changed again in May 2020 when, by deactivating their radars and switching to electro-optical sensors, the LNA's air defense system operators avoided Turkish electronic warfare jamming and detection.[127] Consequently, "several Turkish combat drones [operated by the GNA] were shot down . . . [although] it was already too late to have a real impact on the battlefield dynamics."[128]

Finally, traditional military assets and equipment are still fundamental for both enabling drone strikes and fighting against capable adversaries. In the battles for western coastal Libya, drone operations proved "useful, but not decisive."[129] The final outcome of the military campaign—the end of the siege of Tripoli—was largely determined by Turkey's intervention on the side of the GNA, and by the lack of foreign support for the LNA.[130]

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123. "SOHR Says Total Number of Syrian Mercenaries in Libya Has Risen to 15,800," *Libya Review*, July 10, 2020, https://libyareview.com/4677/sohr-says-total-number-of-syrian-mercenaries-in-libya-has-risen-to-15800/; and H. Tayea, "SOHR: Turkey Deployed 15,300 Turkish-Backed Mercenaries in Libya," *See News*, July 5, 2020, https://see.news/sohr-number-of-syrian-mercenaries-in-libya-rises-to-153/.
124. Pack and Pusztai, "Turning the Tide," p. 9.
125. Joseph Trevithick, "Russian MiG-29 and Su-24 Combat Jets Caught In-Flight at Libyan Base," *Warzone*, June 18, 2020, https://www.thedrive.com/the-war-zone/34193/new-imagery-catches-russian-mig-29-and-su-24-combat-jets-in-flight-at-libyan-air-base.
126. "Turkish 'Hawk' Deployed in Tripoli," *Itamilradar*, January 18, 2020, https://www.itamilradar.com/2020/01/18/turkish-hawk-deployed-in-tripoli/; and Fishman and Hiney, "What Turned the Battle for Tripoli?"
127. Pack and Pusztai, "Turning the Tide," p. 12.
128. Ibid.
129. Gady, "Useful, but Not Decisive."
130. Pack and Pusztai, "Turning the Tide," p. 12; and Kington, "Libya Is Turning into a Battle Lab for Air Warfare." According to media sources, "Unconfirmed reports claim GNA's Turkey-supplied Bayraktar TB2 and Anka-S armed drones to have destroyed at least 20 Pantsir air defense

The Drone War in the Syrian Civil War, 2011–2020

Following the Arab Spring in 2011, unrest in Syria evolved into a civil war. The Syrian civil war can be divided into three different campaigns: the clash between the Syrian government, its allies, and various anti-government forces, including ISIS and al-Nusra; Turkey's military operations against the Kurds in northern Syria; and the international coalition efforts to defeat ISIS.[131] Russia, Iran, and Hezbollah intervened in support of the Bashar al-Assad regime, whereas the United States, Turkey, and Saudi Arabia, among others, supported different anti-government forces and, in the case of the United States and its allies, also fought against ISIS.[132]

Drones were used extensively in all three campaigns, and Syria has been described as "the most drone-dense conflict to date," with "military, commercial, hobbyist, and homemade models taking to the skies on all sides."[133] As in Libya, drone usage in Syria attracted significant attention and led to speculations about their revolutionary implications for modern warfare.[134] As we show in this section, however, the Syrian case does not lend support to the drone revolution thesis: drones did not grant an offensive advantage, they did not strengthen militarily weaker actors, and they did not cancel close combat.

OFFENSIVE ADVANTAGE

If drones enjoy an offensive advantage, they should either experience limited attrition or manage to successfully carry out attacks despite the enemy's air defense systems. As in Libya, our research indicates that this was also not the case in Syria. In December 2013, Syrian anti-government rebels shot down

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systems, ground targets and warplanes," cited in Aishwarya Rakesh, "Turkish Drones in Lybia, EW Systems in Syria 'Game Chaning': UK Defense Secretary," *Defense World*, July 15, 2020, https://www.defenseworld.net/news/27424/Did_UK_s_Defense_Secretary_Praise_Turkey_s_Drones__EW_Systems_#.X9DmtC1aau4. See also Alex Gatopoulos, "'Largest Drone War in the World': How Airpower Saved Tripoli," *Al Jazeera*, May 28, 2020, https://www.aljazeera.com/news/2020/5/28/largest-drone-war-in-the-world-how-airpower-saved-tripoli.

131. The three campaigns overlap significantly, but this distinction among the three campaigns is analytically useful for understanding the differences in how multiple actors have used drones throughout the Syrian conflict.

132. Christopher Phillips, *The Battle for Syria: International Rivalry in the New Middle East* (New Haven, Conn.: Yale University Press, 2016).

133. Dan Gettinger, *Drones Operating in Syria and Iraq* (Annandale-on-Hudson, N.Y.: Center for the Study of the Drone, Bard College, December 2016), pp. 14–15.

134. Larry Friese, "Emerging Unmanned Threats: The Use of Commercially-Available UAVs by Armed Non-state Actors," Special Report No. 2 (Perth, Australia: Armament Research Services, February 2016), https://armamentresearch.com/wp-content/uploads/2016/02/ARES-Special-Report-No.-2-Emerging-Unmanned-Threats.pdf; Petkova, "Turkish Drones—A 'Game Changer' in Idlib"; and Fukuyama, "Droning On in the Middle East."

Iran's small UAV Yasir in Qalamoun, and from 2015 to 2019, both Turkish and U.S. air defense systems repeatedly shot down several heavier Iranian drones such as the Shaded 129.[135] Similarly, Russia's Orlan-10 drones have been decimated by both the Turkish air defense systems and even the poorly equipped Jaish al-Izzah rebel forces.[136] For instance, in 2017, drones were reportedly "dropping like flies from the sky."[137]

During the Syrian civil war, Russian air defense systems suffered significant losses, leading many to conclude that drones have an undisputed offensive advantage.[138] Available evidence warrants caution against drawing such conclusions. On the one hand, Russian air defense systems neutralized most drone threats. In January 2018, for instance, Russian short-range air defense systems destroyed seven incoming unmanned vehicles, and "Russian specialists of the electronic warfare units managed to seize control of the remaining drones" launched by anti-Assad groups against Russia's bases in Tartus and Khmeimim.[139] From 2018 to 2020, Russian air defenses disabled over 150 drones, and in 2019 alone, Russia neutralized approximately sixty drone-and-missile attacks against its Khmeimim air base.[140] Similarly, during the Turkish counteroffensive in March 2020, Syria deployed Russian short-range air defense systems in Idlib, and in the span of few days, its forces shot down ten Turkish drones and allegedly "stabilized the balance in the battlefield."[141] On the other hand, Russian air defense systems could not always intercept in-

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135. Gettinger, *Drones Operating in Syria and Iraq*, pp. 7–8; Guillaume Lasconjarias and Hassan Maged, "Fear the Drones: Remotely Piloted Systems and Non-state Actors in Syria and Iraq," Research Paper No. 77 (Paris: Institut de Recherche Stratégique de l'Ecole Militaire, September 2019), p. 6; and "How U.S. F-15E Drone Shoot-Down Changed Air Game in Syria," *Aviation Week Intelligence Network*, September 14, 2017, https://aviationweek.com/defense-space/aircraft-propulsion/how-us-f-15e-drone-shoot-down-changed-air-game-syria.
136. "Turkish PM Davutoglu Says Downed Drone Was Russian-Made: TV," Reuters, October 19, 2015, https://www.reuters.com/article/us-mideast-crisis-syria-turkey-idUSKCN0SD12620151019. See also Gettinger, *Drones Operating in Syria and Iraq*, p. 10.
137. Tom Cooper, "Drones Are Dropping Like Flies from the Sky Over Syria," *War is Boring*, June 22, 2017, https://warisboring.com/drones-are-dropping-like-flies-from-the-sky-over-syria/. See also Stein, "Say Hello to Turkey's Little Friend."
138. There is evidence of successful attacks against short-range systems such as the Pantsir-S and Buk-M1-2 (NATO reporting name: SA-17 Grizzly), as well as medium-range systems such as surface-to-air missile batteries, the S300 (SA-10 Gramble), and the S-400 Triumpf (SA-21 Growler).
139. Ridvan Bari Urcosta, "The Revolution in Drone Warfare: The Lessons from the Idlib De-Escalation Zone," *Journal of European, Middle Eastern, & African Affairs*, Vol. 2, No. 3 (Fall 2020), p. 51.
140. Sameer Joshi, "Drone Swarms: The Next Evolution in Warfare," *Raksha Anirveda*, February 8, 2021, http://www.raksha-anirveda.com/drone-swarms-the-next-evolution-in-warfare/; and Urcosta, "The Revolution in Drone Warfare," p. 51.
141. Hasan Hiz, "SİHA'lar İdlib harekatını tarihe geçirdi: 'Bu inanılır gibi değil, tanksavar kullanmaya kalksanız aylar sürer'" [UAVs made the Idlib operation historical: "This is unbelievable, it would take months if you tried to use anti-tank"] *Yeni Safak* [New Dawn], February 29,

coming drones or survive their attacks. As we discuss in the following section, however, this ineffectiveness had more to do with force employment than with the capabilities of drones.

LEVELING EFFECT

If the drone revolution thesis is correct, drones should have strengthened the weaker actors in Syria. In fact, as in Libya, this was not the case. First, both rebel groups and non-state actors operated drones, an epilogue that many interpreted as revolutionizing military affairs. But most drones had little impact on combat outcomes. ISIS drones, for instance, were easily neutralized and, overall, they imposed relatively limited damage and losses on Russian armed forces and equipment.[142] Similarly, Syrian rebel groups employed their small and rudimentary UAVs mostly for surveillance or for dropping small bombs with limited effects on the battlefield.[143]

Second, drones have amplified rather than reduced asymmetries in military power. For instance, U.S. armed forces used their UAVs against ISIS for targeted killings, to strike light armored vehicles, to hunt snipers, and to detect concealed explosive devices.[144] Similarly, Turkish drones such as the Bayraktar TB2 successfully carried out these types of missions against poorly equipped adversaries such as Kurdish rebel groups.[145]

Third, weaker actors did not turn to drones to offset combat losses or their

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2020, https://www.yenisafak.com/dunya/sihalar-idlib-harekatini-tarihe-gecirdi-bu-inanilir-gibi-degil-tanksavar-kullanmaya-kalksaniz-aylar-surer-3527623.

142. Thomas Grove, "Drone Attacks on Russian Bases in Syria Expose Security Holes," *Wall Street Journal*, January 15, 2018, https://www.wsj.com/articles/drone-attacks-on-russian-bases-in-syria-expose-security-holes-1516017608; T. S. Allen, Kyle Brown, and Jonathan Askonas, "How the Army Out-Innovated the Islamic State's Drones," *War On the Rocks*, December 21, 2020, https://warontherocks.com/2020/12/how-the-army-out-innovated-the-islamic-states-drones/; and Asaad Almohammad and Anne Speckhard, *ISIS Drones: Evolution, Leadership, Bases, Operations, and Logistics* (Washington, D.C.: International Center for the Study of Violent Extremism, 2017), p. 1.

143. Gideon Grudo, "ISIS UAS Capabilities Choked, Posing Little Threat in 2018," *Air Force Magazine*, January 26, 2018, https://www.airforcemag.com/isis-uas-capabilities-choked-posing-little-threat-in-2018/; and Louisa Loveluck and Thomas Gibbons-Neff, "Islamic State Is 'Fighting to the Death' as Civilians Flee Raqqa," *Washington Post*, August 8, 2017, https://www.washingtonpost.com/world/middle_east/in-raqqa-a-battle-of-attrition-as-civilians-flee-in-shock/2017/08/07/1e814f9e-78f7-11e7-803f-a6c989606ac7_story.html.

144. Adam J. Hebert, "In Case You Missed It: Airpower Killed ISIS," *Air Force Magazine*, January 29, 2018, https://www.airforcemag.com/article/in-case-you-missed-it-airpower-killed-isis/; and W. J. Hennigan, "US Leans on Risky Drone Strikes in Urban Syrian Fight," *Stars and Stripes*, August 19, 2017, https://billingsgazette.com/ap/national/us-leans-on-risky-drone-strikes-in-urban-syrian-fight-copy/article_1d2dd1D.C.-76f0-54a4-b9a7-61dfcf758c19.html.

145. Turkish drones employ Mini Akıllı Mühimmat (MAM), which are thermobaric smart micro munition. See Scott Crino and Andy Dreby, "Turkey's Drone War in Syria—A Red Team View," *Small Wars Journal*, April 16, 2020, https://smallwarsjournal.com/jrnl/art/turkeys-drone-war-syria-red-team-view; and Christian Clausen, "Combat RPAs Integral in Defeating ISIS," *Air Force*

overall inferiority. The Assad regime, the Syrian Kurds, ISIS, and other rebel forces were each on the verge of collapse at different stages of the conflict, but they did not quickly produce, procure, or deploy drones to launch counteroffensives.[146] In contrast, regional and great powers such as Iran and Russia deployed their troops and traditional military assets to prop up the Syrian government, while the United States supported Syrian Kurds and other rebel forces to resist ISIS and the Syrian government.[147] Although analysts have discussed the use of drones by ISIS, as the group became encircled, it did not rely on military drones to oppose enemy advances. Finally, foreign actors produced, supplied, and operated most of the drones that were used in the Syrian conflict, a finding that contradicts the drone revolution thesis.[148]

CLOSE COMBAT AND FORCE EMPLOYMENT

In the case of Syria, we do not find evidence that close combat disappeared or that combat proficiency became less important in determining battle outcomes.

First, the intense and extensive use of close combat during the Syrian civil war constitutes a further disconfirmation of the drone revolution thesis.[149] Overall, the conflict has produced between 100,000 and 500,000 fatalities, and "more than half of the pre-war population [has] been displaced, with 6.2 million people internally displaced and 5.3 registered as refugees, primarily in neighboring countries but increasingly as a global diaspora."[150] This destruc-

News Service, December 5, 2017, https://www.af.mil/News/Article-Display/Article/1388206/combat-rpas-integral-in-defeating-isis/.

146. Among the other sources, we consulted Carla E. Humud and Christopher M. Blanchard, "Armed Conflict in Syria: Overview and U.S. Response" (Washington, D.C.: Congressional Research Service, 2020); and Becca Wasser et al., *The Air War against the Islamic State: The Role of Airpower in Operation Inherent Resolve* (Santa Monica, Calif.: RAND, 2021).

147. Samuel Charap, Elina Treyger, and Edward Geist, *Understanding Russia's Intervention in Syria* (Santa Monica, Calif.: RAND, 2019); Seth G. Jones, ed., *Moscow's War in Syria* (Washington, D.C.: Center for Strategic and International Studies [CSIS], 2020), pp. 19–20; and Michael Kofman, "Syria and the Russian Armed Forces: An Evaluation of Moscow's Military Strategy and Operational Performance," in Robert E. Hamilton, Chris Miller, and Aaron Stein, eds., *Russia's War in Syria: Assessing Russian Military Capabilities and Lessons Learned* (Philadelphia, Pa.: Foreign Policy Research Institute, 2020), pp. 35–65.

148. Many analysts have emphasized the use of drones by non-state actors like Hezbollah, ISIS, and al-Nusra. But these actors deployed only mini and micro commercial drones (Class I in Gettinger's *The Drone Databook*) that have limited ranges, speeds, and payloads for terror-like attacks or ambushes against individual targets.

149. Joseph Holliday, *The Assad Regime: From Counterinsurgency to Civil War*, Middle East Security Report No. 8 (Washington, D.C.: Institute for the Study of War, 2013); and Isabel Nassief, *The Campaign for Homs and Aleppo*, Middle East Security Report No. 17 (Washington, D.C.: Institute for the Study of War, 2014).

150. UN General Assembly, *Report of the Independent Commission of Inquiry on the Syrian Arab Republic*, A/HRC/46/54, February 22–March 19, 2021, p. 4, https://undocs.org/A/HRC/46/54; and

tion was not the product of drone strikes, but the result of continuous cycles of advances, sieges, frontal clashes, retreats, and counteroffensives as epitomized by several key battles, such as in Damascus, Walamous, al-Yaarybiyah, Aleppo, Idlib, Yarmouk, and Raqqa.[151] Drones, and more generally the indiscriminate use of air power by Syrian armed forces, along with their Iranian and Russian supporters through artillery, attack helicopters, and air-to-ground bombers, failed to eliminate close combat.[152] In fact, most campaigns continued their strategies of sieges, starvation, and storming towns and cities.[153] Moreover, ISIS and other rebel groups relied extensively on guerrilla tactics and modern combat approaches to penetrate enemy lines and gain territory.[154] Finally, both the Syrian government and Iranian forces fired ballistic missiles against the rebels in 2012, 2017, and 2021, while the Syrian government used more than 80,000 barrel bombs and conducted several attacks with chemical weapons from 2012 to 2021.[155] If drones are so easy to use, so quick and cheap to produce and procure, and so effective, why did the actors fighting in Syria instead use economically and politically more expensive alternatives?

Second, combat skills and proficiency remained fundamentally important throughout the conflict. The alleged vulnerability of Russian air defense systems to rebels' drones is an ideal instance to test the effectiveness of drones. Although it is challenging to detect, track, and engage small targets flying at low altitude, especially for ground-based, long-range systems, asymmetries in the modern system of force employment explain the successes and failures of drone operations.[156] On the one hand, the limited experience and relatively poor skills of Syrian personnel at operating air defense systems exposed their

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"A Decade of War in Syria: 10 Years of Increasing Humanitarian Needs" (Geneva: Médecins Sans Frontières, 2021).

151. Erwin van Veen et al., *Band-Aids, Not Bullets: EU Policies and Interventions in the Syrian and Iraqi Civil Wars*, Conflict Research Unit Report (The Hague: Clingendael Institute, 2021), pp. 15–22.

152. Ralph Shield, "Russian Airpower's Success in Syria: Assessing Evolution in Kinetic Counterinsurgency," *Journal of Slavic and Military Studies*, Vol. 31, No. 2 (2018), pp. 214–239, https://doi.org/10.1080/13518046.2018.1451099; Anton Lavrov, *The Russian Air Campaign in Syria: A Preliminary Analysis* (Arlington, Va.: Center for Naval Analysis, 2018); and Timothy Thomas, *Russian Lessons Learned in Syria: An Assessment* (McLean, Va.: MITRE Center for Technology and National Security, 2020).

153. Christopher Kozak, *"An Army in All Corners": Assad's Campaign Strategy in Syria*, Middle East Security Report No. 26 (Washington, D.C.: Institute for the Study of War, 2015).

154. Omar Ashour, *How ISIS Fights: Military Tactics in Iraq, Syria, Libya, and Egypt* (Edinburgh: Edinburgh University Press, 2021).

155. Syrian Network for Human Rights [SNHR], *In Nine Years, the Syrian Regime Has Dropped Nearly 82,000 Barrel Bombs, Killing 11,087 Civilians, Including 1,821 Children* (UK: SNHR, April 15, 2021), https://reliefweb.int/report/syrian-arab-republic/nine-years-syrian-regime-has-dropped-nearly-82000-barrel-bombs-killing; and Daryl Kimball and Kelsey Davenport, "Timeline of Syrian Chemical Weapons Activity, 2012–2021," Arms Control Association, May 2021, https://www.armscontrol.org/factsheets/Timeline-of-Syrian-Chemical-Weapons-Activity.

156. Guy Plopsky, "Russia's Air Defenses in Syria: More Politics than Punch," Begin-Sadat Center

positions to enemy fire.[157] On the other hand, the Syrian government's adversaries proved remarkably skilled at suppressing enemy air defenses. The battle for Idlib in northeast Syria from December 2019 to March 2020 shows the importance of the modern system of force employment in air warfare. Turkish troops effectively used different platforms, systems, and countermeasures against Syrian surface-to-air batteries: They geolocated Syrian soldiers by hacking their phones, they deceived and blinded Russian antiair defense systems using their advanced KORAL multifunctional electronic warfare systems, and they used their Bayraktar TB2 and Anka-S drones to attack and destroy targets or to provide the enemy's geocoordinates to artillery systems (e.g., T-155 Firtina).[158] But when the Syrian Army and its local allies adopted stricter operational security measures, such as stopping cell phone usage and switching to paper-based communications, Turkey abruptly lost its military advantage as its sensors could no longer easily track and detect enemy targets.[159]

Importantly, Turkey's large-scale and effective use of drones in coordinated squadron attacks in the battle for Idlib was more the result of Turkish troops' mastery of the modern system in exploiting geographical and topographical factors than of drones' features.[160] Idlib's proximity to the Turkish border made it relatively easy for Turkish armed forces to conduct ISR target acquisition and sequential strikes. By using squadron drone attacks, Turkey could achieve "high precision long-range strikes, enabling Turkey to bypass the Idlib airspace yet managing to inflict heavy casualties to Syrian Arab Army targets."[161] As the former director of international affairs for Turkey's

for Strategic Studies, October 18, 2017, https://besacenter.org/perspectives-papers/russia-air-defense-syria/.

157. John V. Parachini and Peter A. Wilson, "Drone-Era Warfare Shows the Operational Limits of Air Defense Systems," *RAND Blog*, July 2, 2020, https://www.rand.org/blog/2020/07/drone-era-warfare-shows-the-operational-limits-of-air.html.

158. Urcosta, "The Revolution in Drone Warfare," p. 52; Alex Gatopoulos, "Battle for Idlib: Turkey's Drones and a New Way of War," *Al Jazeera*, March 3, 2020, https://www.aljazeera.com/news/2020/3/3/battle-for-idlib-turkeys-drones-and-a-new-way-of-war; Taşdan, "Turkish EW Systems"; and Bakir, "Turkey's Electronic Warfare Capabilities." Turkish troops first transmitted data to drones (the TAI Anka) operating as communication relays, which in turn then passed this data to combat drones at longer distances.

159. Urcosta, "The Revolution in Drone Warfare," p. 52.

160. Petkova, "Turkish Drones—A 'Game Changer' in Idlib." See also Gatopoulos, "Battle for Idlib." We cross-checked data on the Turkish Gendarmerie's equipment list with primary and secondary resources to estimate that Turkey deployed about twenty ANKA-S and Bayraktar TB2 drones in Syria.

161. Dylan Nicholson, "'Revolutionary' Warfare or Good Marketing: Turkey's Syria Drone Strikes," *Defence Connect*, March 9, 2020, https://www.defenceconnect.com.au/strike-air-combat/5709-revolutionary-warfare-or-good-marketing-turkey-s-syria-drone-strikes.

Undersecretariat for Defense Industries noted, "You take off from Turkey and are there within minutes. Targets are also very close together, which means you don't have to spend hours looking for them."[162] Moreover, Syrian armed forces displayed little proficiency in concealing their air defense systems, which were exposed to Turkey's air strikes.[163]

Armenia-Azerbaijan Conflict over Nagorno-Karabakh, 2020

Nagorno-Karabakh is a region internationally recognized as being part of Azerbaijan. Since the 1991–1994 war, it has been under Armenian control. On September 27, 2020, Azerbaijan tried to revert this situation with what became known as the "44-day war."[164] Azerbaijan's extensive and successful reliance on drones led many analysts and scholars to claim that this military confrontation represented a turning point in warfare.[165] According to some, "Azerbaijan's drones owned the battlefield in Nagorno-Karabakh."[166] Others speculated that the systematic use of drones led to the demise of the tank, and that drones were the decisive factor in the war.[167] As in the previous cases of Libya and Syria, the empirical record does not support this interpretation. In contrast, this case further strengthens the validity of the modern system of force employment to understand success and failure of drone operations.

OFFENSIVE ADVANTAGE

In the early days of the conflict, Azeri drones suppressed Armenia's mobile air defenses, lending prima facie support to speculations about an ensuing drone

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162. Ibid.
163. Ibid.
164. Nikola Mikovic, "Azerbaijan Watches Closely the Russian Invasion of Ukraine," *Interpreter*, Lowy Institute, March 11, 2022, https://www.lowyinstitute.org/the-interpreter/azerbaijan-and-russian-invasion-ukraine.
165. James Rogers, "Iran and Turkey Have Become Drone Powers," *Monkey Cage* blog, *Washington Post*, January 28, 2021, https://www.washingtonpost.com/politics/2021/01/28/iran-turkey-have-become-drone-powers/.
166. Robyn Dixon, "Azerbaijan's Drones Owned the Battlefield in Nagorno-Karabakh—and Showed Future of Warfare," *Washington Post*, November 11, 2020, https://www.washingtonpost.com/world/europe/nagorno-karabkah-drones-azerbaijan-aremenia/2020/11/11/441bcbd2-193d-11eb-8bda-814ca56e138b_story.html.
167. "The Azerbaijan-Armenia Conflict Hints at the Future of War," *Economist*, October 8, 2020, https://www.economist.com/europe/2020/10/08/the-azerbaijan-armenia-conflict-hints-at-the-future-of-war; Peter Suciu, "Does the Nagorno-Karabakh Conflict Prove the Tank is Toast?" *National Interest*, October 5, 2020, https://nationalinterest.org/blog/buzz/does-nagorno-karabakh-conflict-prove-tank-toast-170155; and Henry Foy, "Drones and Missiles Tilt War with Armenia in Azerbaijan's Favour," *Financial Times*, October 28, 2020, https://www.ft.com/content/6acddc7d-cda5-44b2-9e5c-f6863f7bb9e7.

revolution in military affairs.[168] Azerbaijan, however, used some of the same drones that had been employed and shot down in Libya and Syria. This variation in outcome begs the question: Why did drones succeed in Nagorno-Karabakh but fail in other theaters? The answer lies in the superiority of Azerbaijan vis-à-vis Armenia in implementing the modern system of force employment in air warfare.

First, Armenia did not possess a layered integrated air defense system capable of addressing a multiplicity of threats at both short and long ranges as well as low and high altitudes. Second, its personnel lacked the necessary skills. Third, Armenia's surface-to-air missile batteries were mostly obsolete, Soviet-era (1960s–1970s) platforms, which are significantly less capable than many of the air defense systems deployed by Turkey and the UAE in Libya, and by Russia in Syria.[169] Some of these Soviet-era systems cannot detect, track, or engage small targets because they lack advanced signal processing functions.[170] Other systems have these capabilities, but their electronic counter-

168. In the initial phase of war, Azerbajan's drones, mostly armed with Rocketsan MAM-L Smart Munitions, destroyed around sixty air defense systems, primarily 9K33 OSA and 9K35 Strela. The Turkish-made TB2s and the Israeli-made Harpy and Harop also destroyed more advanced Russian-made S-300s, besides several Armenian T-72 tanks and armored vehicles. Can Kasapoglu, "Analysis—Five Key Military Takeaways from Azerbaijani-Armenian War," *Anadolu Agency*, October 30, 2020, https://www.aa.com.tr/en/analysis/analysis-five-key-military-takeaways-from-azerbaijani-armenian-war/2024430; Stijn Mitzer et al., "The Fight for Nagorno-Karabakh: Documenting Losses on the Sides of Armenia and Azerbaijan," *Oryx* blog, September 27, 2020, https://www.oryxspioenkop.com/2020/09/the-fight-for-nagorno-karabakh.html; Stijn Mitzer et al., "The Conqueror of Karabakh: The Bayraktar TB2," *Oryx* blog, September 27, 2021, https://www.oryxspioenkop.com/2021/09/the-conqueror-of-karabakh-bayraktar-tb2.html; and Shaan Shaikh and Wes Rumbaugh, *The Air and Missile War in Nagorno-Karabakh: Lessons for the Future of Strike and Defense* (Washington, D.C.: CSIS, December 8, 2020), https://www.csis.org/analysis/air-and-missile-war-nagorno-karabakh-lessons-future-strike-and-defense.

169. Michael Kofman and Leonid Nersisyan, "The Second Nagorno-Karabakh War, Two Weeks In," *War on the Rocks*, October 14, 2020, https://warontherocks.com/2020/10/the-second-nagorno-karabakh-war-two-weeks-in/. The systems are the 2K11 Krug, 9K33 Osa, 2K12 Kub, and 9K35 Strela-10, S-300P. Alexander Stronell, "Learning the Lessons of Nagorno-Karabakh the Russian Way," IISS, March 10, 2021, https://www.iiss.org/blogs/analysis/2021/03/lessons-of-nagorno-karabakh.

170. For instance, at the start of the conflict, Armenia possessed the upgraded variants of the Soviet-made S-300P air defense system (the S-300PT and S-300PS). This type of air defense system was commissioned in 1978, and most states in the world (except Armenia, Belarus, and Ukraine) have decommissioned them for more modern ones. Armenia bought these systems from Russia after 1999. Originally vulnerable against small targets flying at low altitudes, these systems were upgraded (e.g., the S-300PT equipped with 5V55KD surface-to-air missiles and semi-active radar homing guidance mode). Still, these new variants have limited capabilities to detect, identify, and track small and slow targets. On the capabilities and limitations of the S-300P, see Steven J. Zaloga, *Soviet Air Defence Missiles: Design, Development, and Tactics* (London: Jane's, 1989), pp. 111–117; and Gustav Gressel, "Military Lessons from Nagorno-Karabakh: Reason for Europe to Worry," *Wider Europe* blog, European Council on Foreign Relations, November 24, 2020, https://ecfr.eu/article/military-lessons-from-nagorno-karabakh-reason-for-europe-to-worry/.

countermeasures are not updated, making them vulnerable to jamming by enemy electronic warfare systems.[171] Fourth, Armenia's limited electronic warfare capabilities could not jam or hack Azeri communications, on which drones' remote control depends.[172] Fifth, because of the limited data integration between different sensors and systems, Armenian short-range air defense systems sometimes detected but did not intercept Azeri drones, which exploited altitude to reduce exposure to enemy fire.[173] Finally, we observe a clear gap in concepts of operations, proficiency, and skill between Armenian and Azeri armed forces. Azeri forces employed tactics and technologies to deceive, blind, locate, and destroy Armenian air defenses, which permitted Azeri drones to penetrate Armenian air space and act with relative impunity.[174] Specifically, Azerbaijan converted multiple Soviet-era Antonov An-2 light aircraft into remotely piloted aircraft and used them as baits to detect and locate Armenian air defense systems.[175] Armenian air defenses fell into the trap, and by illuminating these decoys, their acquisition radars gave up their position, thus becoming themselves targets of Azerbaijan's anti-radiation missiles and loitering munitions.[176] Together with the Turkish electronic warfare system, which blinded the Armenian radar systems that were still functioning, these tactics and technologies allowed Azeri drones to penetrate Armenian air defense systems and strike targets in Nagorno-Karabakh.[177]

In sum, the deficiencies and vulnerabilities of Armenia's air defense sys-

171. These counter-countermeasures attempt to minimize the enemy's capacity to interfere with a radar's function. Moreover, while some of these radar systems are able to limit detection by enemy antiradiation missiles (e.g., low-probability of intercept), others do not, which might explain why they succumbed to Turkish bait tactics.
172. Gressel, "Military Lessons from Nagorno-Karabakh."
173. The integration of data among different air defense systems would have permitted Armenia to detect incoming threats with one system and engage it with a different one. For instance, "TB2s flew too high for these systems (like 2K11 Krug, 9K33 Osa, 2K12 Kub, and 9K35 Strela-10) to intercept even if they were able to detect these relatively small aircraft." Quoted in Shaikh and Rumbaugh, *The Air and Missile War in Nagorno-Karabakh*.
174. Ron Synovitz, "Technology, Tactics, and Turkish Advice Lead Azerbaijan to Victory in Nagorno-Karabakh," *Radio Free Europe/Radio Liberty*, November 13, 2020, https://www.rferl.org/a/technology-tactics-and-turkish-advice-lead-azerbaijan-to-victory-in-nagorno-karabakh/30949158.html. Armenia shot down only one Azerbaijani Aerostar Surveillance UAV, eleven IAI Harop Loitering Munitions, three SkyStriker Loitering Munitions, one Orbiter 1K Loitering Munition, two Bayraktar TB2 UCAVs, and eight unknown UAVs. Data are from Mitzer et al., "The Fight for Nagorno-Karabakh."
175. In late August 2020, Baku owned approximately sixty converted An-2s stationed at Yevlakh Airport. Benjamin Fogel and Andro Mathewson, "The Next Frontier in Drone Warfare? A Soviet-Era Crop Duster," *Bulletin of the Atomic Scientists*, February 10, 2021, https://thebulletin.org/2021/02/the-next-frontier-in-drone-warfare-a-soviet-era-crop-duster/.
176. Synovitz, "Technology, Tactics, and Turkish Advice"; and Fogel and Mathewson, "The Next Frontier in Drone Warfare?"
177. Taşdan, "Turkish EW Systems."

tems, together with the infrastructural and operational support that Turkey provided Azerbaijan, explain why Azeri drones managed to penetrate and operate within Armenian air space with relative impunity in the early phase of the conflict.[178] The situation changed later in the war, when Armenia fielded more advanced systems, such as the Russian Polye-21 electronic warfare system, which proved very effective.[179] Similarly, Russian forces used the Krasukha electronic warfare system based in Gyumri, Armenia, to interdict Azeri deep reconnaissance and to jam the signals linking the drones to their guidance stations.[180] Finally, Armenian armed forces used the Buk-M1-2, Buk-M2, and Tor-M2KM air defense systems to successfully intercept and shoot down some enemy drones.[181] With these more advanced air defense systems, Azeri drones' offensive advantage waned, but these systems "were deployed too late in the conflict, limited in number, and vulnerable to attack themselves" to reverse the course of the war.[182]

LEVELING EFFECT

Far from being the weapon of te weak or an equalizing force, also in the case of Nagorno-Karabakh, drones systematically favored the stronger side, that is, Azerbaijan. In the two decades preceding the conflict, Azerbaijan had significantly increased its defense spending thanks to its natural gas reserves and sustained economic growth.[183] As a result, whereas in 2000 Armenia and Azerbaijan spent roughly the same for defense ($152 million and $141 million, respectively), in 2020 Azerbaijan outspent Armenia by three times ($2.2 billion and $638 million, respectively).[184] Consequently, at the outset of the conflict, Azerbaijan's armed forces were qualitatively and quantitatively superior to Armenia's.[185]

Second, not only is Azerbaijan economically and militarily more powerful

178. Gressel, "Military Lessons from Nagorno-Karabakh."
179. Shaikh and Rumbaugh, *The Air and Missile War in Nagorno-Karabakh*.
180. Stephen Bryen, "Russia Knocking Turkish Drones from Armenian Skies," *Asia Times*, October 26, 2020, https://asiatimes.com/2020/10/russia-knocking-turkish-drones-from-armenian-skies/.
181. Leonid Nersisyan, "Iskhod na sushe, opredelennoy v vozdukhe" [Exodus on land, determined in the air], in Ruslan N. Pukhov, ed., *Burya na Kavkaze* [Storm in the Caucasus] (Moscow: Moscow Center for Analysis of Strategies and Technologies, 2021), p. 67.
182. Shaikh and Rumbaugh, *The Air and Missile War in Nagorno-Karabakh*.
183. SIPRI Military Expenditure Database (Stockholm: Stockholm International Peace Research Institute, 2022), https://www.sipri.org/databases/milex.
184. Ibid.
185. Natalia Freyton, "Armenia-Azerbaijan War: A First-Hand Account," *Raksha Anirveda*, February 14, 2021, https://www.raksha-anirveda.com/armenia-azerbaijan-war-a-first-hand-account/; and IISS, *The Military Balance 2020* (London: Routledge, 2020), p. 183.

than Armenia, but it also received extensive support from a regional power, Turkey, whose help during the Armenia-Azerbaijan conflict over Nagorno-Karabakh was instrumental in its systematic employment of drones. According to some sources, Turkish commanders oversaw the drone campaign.[186] Turkish support included the provision of drones, electronic warfare units, aircraft for target acquisition, long-range artillery, skilled Turkish troops that operated these platforms, and the transportation of Syrian fighters to the theater of operation for ground combat.[187] Additionally, Turkey shared its expertise in and experience with employing modern tactics and operational concepts with Azerbaijan, which used decoys to detect and strike enemy ground-based air defense systems; employed special operations forces to penetrate deep inside enemy territory so that they could provide target geocoordinates through laser-designators for precision strikes; and coordinated the use of different systems, such as drones and long-range artillery.[188]

In addition to being the weaker side, Armenia did not receive any significant external support. In contrast to the drone revolution thesis, it did not turn to drones to redress its numerical and qualitative military inferiority on the battlefield. In fact, Armenia deployed a relatively modest UAV fleet that consisted of small indigenous systems for reconnaissance such as the X-55, the Krunk, the Russian-made Orlan-10, and the HRESH loitering munition.[189] As a weapon of last resort, however, Armenia turned to ballistic missiles against Azerbaijan—a counterintuitive epilogue for the drone revolution thesis, which assumes that drones are affordable and effective.[190] With regard to Azerbaijan, the drones it used were foreign made and supplied: the Turkish Bayraktar TB2 UAVs (number unknown); the Israeli-made ISR drones Hermes-900 (two), Hermes-450 (ten), Heron (five), Aerostar (fourteen), and Searcher (five); and the Israeli loitering munitions Harop (fifty), Orbiter 1K (eighty), Orbiter-3 (ten), and SkyStriker (one-hundred).[191]

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186. Antov V. Lavrov, "Sorok cetiri dnya vtoroy Karabakhskoy"[Forty-four days of the second Karabakh] in Pukhov, ed., *Burya na Kavkaze*, p. 51; and Tatevik Hayrapetyan, "How Ilham Aliyev 'Personalizes' the Results of the 2020 Artsakh War," *EVN Report*, September 9, 2021, https://www.evnreport.com/politics/how-ilham-aliyev-personalizes-the-results-of-the-2020-artsakh-war.
187. Freyton, "Armenia-Azerbaijan War"; and Marina Miron and Rod Thornton, "Russia's 'Revenge' after Nagorno-Karabakh: Reprisals in Syria for Turkey's Support of Azerbaijan," *Defence In Depth*, December 7, 2020, https://defenceindepth.co/2020/12/07/russias-revenge-after-nagorno-karabakh-reprisals-in-syria-for-turkeys-support-of-azerbaijan/.
188. Miron and Thornton, "Russia's 'Revenge' after Nagorno-Karabakh."
189. IISS, *The Military Balance 2020*, p. 183; and Shaikh and Rumbaugh, *The Air and Missile War in Nagorno-Karabakh*.
190. Shaikh and Rumbaugh, *The Air and Missile War in Nagorno-Karabakh*.
191. Burak Ege Bekdil, "Azerbaijan to Buy Armed Drones from Turkey," *Defense News*, June 25,

CLOSE COMBAT AND FORCE EMPLOYMENT

Contrary to the expectations of the drone revolution thesis, the deployment of drones on the battlefield did not eliminate close combat, and it did not make traditional force employment elements obsolete. In fact, during the conflict, "many casualties [we]re still inflicted by armor, artillery, and multiple launch rocket systems."[192]

First, far from disappearing, close combat played a key role also in the 2020 Armenia-Azerbaijan conflict. Despite the extensive use of ballistic missiles, loitering and other precision-guided munitions, as well as UAVs, infantry units proved pivotal to holding defensive lines and advancing in the front. Groups of mercenaries and regular forces fought on both sides in World War I–style trenches positioned a few meters away from one another.[193] According to some analysts, Turkey's deployment of Syrian mercenaries in support of Azerbaijan was the game changer.[194] Fighting in coordination with other elements of the force structure, these mercenaries contributed to overwhelming Armenian defensive positions, which ultimately forced Russia to intervene diplomatically.[195] The Battle for Shusha/Shushi City is a telling example: It was "the most important battle of the Nagorno-Karabakh war" because "once Shusha fell, Armenia surrendered and entered a lopsided agreement, ceding massive amounts of their previously held territories."[196] To carry out this attack, about 400 Azeri special operation forces marched for five days through forests and ravines, climbing rocks and cliffs, to reach the city without alerting the enemy's defenses. Once they entered the city, Azeri forces "engaged the defending Armenians at close range in heavy street fighting."[197] Because fog had descended on the city by the time the attack had started, Azeri drones could not be used to destroy or disable Armenian armored vehicles. This allowed the 2,000 Armenian troops to maximize the use of their T-72 tanks and BMP-2 infantry fighting vehicles, in addition to relying on heavy artil-

2020, https://www.defensenews.com/unmanned/2020/06/25/azerbaijan-to-buy-armed-drones-from-turkey/.
192. Kofman and Nersisyan, "The Second Nagorno-Karabakh War."
193. Bethan McKernan, "Trench Warfare, Drones, and Cowering Civilians: On the Ground in Nagorno-Karabakh," *Guardian*, October 13, 2020, https://www.theguardian.com/artanddesign/2020/oct/13/trench-warfare-drones-and-cowering-civilians-on-the-ground-in-nagorno-karabakh.
194. Miron and Thornton, "Russia's 'Revenge' after Nagorno-Karabakh."
195. Ibid. The Syrian mercenaries fought on the front line and suffered a high casualty rate. It is estimated that about 143 Syrians had died by mid-October 2020.
196. John Spencer and Harshana Ghoorhoo, "The Battle of Shusha City and the Missed Lessons of the 2020 Nagorno-Karabakh War," *Modern War Institute*, July 14, 2021, https://mwi.usma.edu/the-battle-of-shusha-city-and-the-missed-lessons-of-the-2020-nagorno-karabakh-war/.
197. Ibid.

lery. As a result, dismounted Azeri special forces had to rely extensively on rocket-propelled grenades, portable antitank guided missiles, multiple launch rocket systems, and artillery.[198] Once again, drones did not erase distance or ground conflict.

Second, drones did not make traditional force employment obsolete. Azeri forces, for instance, skillfully exploited the geography of the conflict to their advantage. Nagorno-Karabakh is a mountainous region. Proximity to mountains and other natural or artificial obstacles significantly degrades the effectiveness of ground-based air defense systems because it interferes with the line of sight between radar and target that is necessary for detection, and it generates unwanted radar returns that make detection more difficult (i.e., "ground clutter"). Azeri forces exploited the morphology of the terrain to limit or delay their exposure to enemy radar and hence minimize the risk of interception.[199] Moreover, as mentioned previously, Azeri forces also effectively employed tactics and technologies aimed at degrading and suppressing Armenian air defense systems.[200]

Geography further proved to be an asset to Azerbaijan's offensive operations. Nagorno-Karabakh is an enclave within Azerbaijan, which means that the latter faced limited logistical and infrastructural challenges. Moreover, by taking control of Gamish Mountain, Azerbaijan gained a strategic position over the road that connects the front and rear of Armenia's operation (i.e., between the cities of Kelbajar and Aghdere).[201] Once Armenia's air defense systems had been neutralized, Azeri drones could then easily destroy any targets transiting on this road.[202] Azerbaijan also effectively employed its special operation forces for its drone operations. Endowed with laser-designators for acquiring valuable but hard-to-detect targets deep inside enemy territory, Azeri special operation forces supported precision strikes against relevant assets such as arms depots and communication centers.[203]

Whereas both sides struggled with certain aspects of modern tactics and operations, Armenian forces appeared to perform comparatively worse. Moreover, the absence of a layered air defense system further hindered Armenia, leaving its ground forces vulnerable to enemy fire.[204] Armenia's problems

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198. Ibid.
199. Kofman and Nersisyan, "The Second Nagorno-Karabakh War."
200. Synovitz, "Technology, Tactics, and Turkish Advice."
201. Ridvan Bari Urcosta, "Drones in the Nagorno-Karabakh," *Small Wars Journal*, October 23, 2020, https://smallwarsjournal.com/jrnl/art/drones-nagorno-karabakh.
202. Ibid.
203. Synovitz, "Technology, Tactics, and Turkish Advice."
204. Also, Armenia took advantage of Azeri tactical and operational deficiencies. Armenia used

were epitomized by mass movements of troops, in the open, during daylight, and without air defense, which left soldiers, vehicles, and platforms exposed to Azeri air power.[205] Once the inherent weakness of the Armenian air defense system became apparent, its troops still implemented insufficient countermeasures and countertactics such as dispersion or camouflage to avoid exposure to enemy fire. For several days after the start of the conflict, in fact, Azeri drones kept targeting Armenian troops in noncombat mode or while convoying.[206] Additionally, Armenia located its air defense systems too forward, in relatively exposed fixed positions in a mountainous region in which air defense is particularly difficult, thus further limiting its effectiveness.[207] This variation in force employment explains why Armenia suffered a high number of casualties, and why about one-third of its tanks were destroyed.[208]

In sum, drones were not a silver bullet in the Armenia-Azerbaijan conflict, in contrast to what many have concluded. This does not mean that drones were unimportant. In fact, when employed with other systems, such as manned aircraft, land-based artillery, electronic warfare systems, and ground-based radars—as Azerbaijan did—they proved to be a significant force multiplier.[209] But without such infrastructural and operational support, drones remained vulnerable to air defense systems, as was the case in Libya and Syria. This is why, "depending on drones, including loitering munitions drones,

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indigenous drones, and later in the conflict it also relied on some of the more sophisticated Russian-made Orlan-10 UAVs, primarily for reconnaissance and target acquisition. But these drone missions had low efficacy against Azeri forces, which had already gained air superiority in the contested territory. Shaikh and Rumbaugh, *The Air and Missile War in Nagorno-Karabakh.*

205. Synovitz, "Technology, Tactics, and Turkish Advice"; Kofman and Nersisyan, "The Second Nagorno-Karabakh War"; and Dixon, "Azerbaijan's Drones Owned the Battlefield in Nagorno-Karabakh."

206. For example, these videos originally shared by Azerbaijan's Ministry of Defense show multiple attacks on fixed and mobile Armenian targets. See Rob Lee (@RALee85), "Warning: graphic video. Azerbaijan has begun releasing TB2 UCAV videos again after last night's strikes on Ganja. This clip shows 20 strikes on NKR soldiers, defensive positions, trucks, and howitzers. Some of this footage could be old. 1155/," Twitter, October 17, 2020, 5:00 p.m., https://twitter.com/RALee85/status/1317499586592858114?s=20; and Rob Lee (@RALee85), "Another Azerbaijani MoD video with 7 TB2 UCAV strikes on NKR/Armenian trucks and troops in cover. The single best thing Armenian/NKR troops can do to avoid these strikes is to not huddle together, even in cover. 1160/," Twitter, October 17, 2020, 6:48 p.m., https://twitter.com/RALee85/status/1317507836470059008?s=20.

207. Kofman and Nersisyan, "The Second Nagorno-Karabakh War"; and Shaikh and Rumbaugh, *The Air and Missile War in Nagorno-Karabakh*. Because of the peculiarities of the Nagorno-Karabakh territory—a partly mountainous, u-shaped enclave surrounded by Azerbaijan—locating air defense systems poses inherent challenges. The greatest distance between the enclave and Azerbaijan's borders is only 70 kilometers.

208. Dixon, "Azerbaijan's Drones Owned the Battlefield in Nagorno-Karabakh."

209. Freyton, "Armenia-Azerbaijan War."

alone would be a strategic mistake. . . . Deployment of these systems depends on the mix of warfare systems and how they are leveraged."[210]

Conclusion

In this article, we have argued that the dominant narrative about an ensuing drone revolution in military affairs has neglected a key transformation in air warfare, what we call the second firepower revolution. Starting from the 1960s, such revolution has led to dramatic improvements in detection, communication, precision, and destruction, making air warfare extremely lethal. The need to avoid enemy lethal firepower has led to a hider-finder competition between air forces and air defenses. Actors that do not master the set of tactics, techniques, procedures, technologies, and capabilities necessary to limit exposure to enemy fire while successfully detecting and targeting the enemy—that is, the modern system of force employment—will suffer severe consequences.

To test the modern system of force employment in air warfare, we have focused on three dependent variables: whether drones yield an offensive advantage; whether they have a leveling effect on existing power imbalances; and whether they cancel close combat. For each of these dependent variables, we have identified the observable implications of the modern system of force employment and of the drone revolution thesis. We have then tested these observable expectations by looking at three recent conflicts in which drones were employed extensively—in Libya, Syria, and the region of Nagorno-Karabakh.

The evidence we have gathered does not support the idea of an ensuing drone revolution. Since we have investigated the conflicts in which drones have been employed more extensively, there is little reason to believe that in other cases, where drones were used more sparingly, we should observe the transformation of warfare that many have described. While the evidence presented in this article is not definitive, our empirical analysis shows that drones have not tilted the military balance toward the offense, they have not had an equalizing effect between strong and weak states, and they have not eliminated close combat. We conclude that drones can be effective if they are operated by skilled military personnel and if they are integrated with other multilayered and conventional systems (e.g., attack and ISR aircraft, radar and electronic warfare systems, artillery, and ground units).

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210. Ibid.

Our analysis contributes to key debates about the study of war, states' defense policies and postures, and the evolution of the international system. First, we have offered a new way to understand the role of drones in modern wars. The theoretical framework we have developed explains why drones proved effective in some conventional conflicts but not in others—a variation in outcome that existing works cannot explain. Moreover, by adapting Biddle's modern system of force employment to the exigencies and idiosyncrasies of air penetration and air defense, our framework provides a way to assess and understand a broader subset of conflicts than Biddle originally envisioned. Our framework also provides guidance beyond the specific case of drone warfare. It can help scholars and practitioners understand the impact of other so-called disruptive and emerging technologies, as well as the dynamics in conventional conflicts, such as the limited use of air power by Russia in the first months of the 2022 invasion of Ukraine.

Second, our framework highlights factors that are often neglected in the academic and public debates about drone warfare and emerging technologies but that are critical for military operations—such as military personnel proficiency, electronic warfare, and air defense systems. With regard to personnel, academics and practitioners have interpreted drone warfare and military robotics as an instance of substitution of labor (soldiers) with capital (advanced technology). But they have largely neglected that "high-technology weapons demand high-quality personnel."[211] With regard to air defense, our article focuses on a set of technologies such as radar systems, antiaircraft guns, and surface-to-air missiles that have had transformational effects on air warfare but that have received scant attention by security studies scholars. To understand the dynamics and outcomes of recent conflicts, our framework focuses on the relative effectiveness of air defense vis-à-vis air penetration rather than on which sides possess armed drones. Our empirical analysis thus offers insights for how both regional and great powers should respond if their allies are targeted by drone attacks. By deploying air defense systems and electronic warfare systems with skilled personnel operating them, regional and great powers can significantly degrade and possibly halt a military offensive that relies heavily on current-generation military drones.

211. Werrell, *Archie to SAM*, p. 174. See also Andrea Asoni et al., "A Mercenary Army of the Poor? Technological Change and the Demographic Composition of the Post-9/11 U.S. Military," *Journal of Strategic Studies*, published online January 2020, https://doi.org/10.1080/01402390.2019.1692660; and Avi Goldfarb and Jon R. Lindsay, "Prediction and Judgment: Why Artificial Intelligence Increases the Importance of Humans in War," *International Security*, Vol. 46, No. 3 (Winter 2021/22), pp. 7–50, https://doi.org/10.1162/isec_a_00425.

Third, our analysis contributes to policy debates on armed forces' restructuring and defense acquisition. States that are considering radical changes in their force structure by shifting toward cheap and small platforms or revisiting their defense postures solely on the basis of technological considerations should be cautious about such actions. For states such as those in Eastern Europe and in South East Asia that face a much more powerful neighbor, our study suggests that current-generation military drones have inherent limitations.[212] For instance, before the start of hostilities between Russia and Ukraine in February 2022, some analysts concluded that Ukraine had "drawn the lesson that it must invest heavily in drone technology, both indigenous and exogenous to counter Russian superiority."[213] Our analysis suggests that drones alone are not sufficient to overcome conventional military inferiority.

Admittedly, our evidence is not definitive, and our analysis has not addressed some important questions. We have limited our focus to the operational level of war, thus omitting the strategic implications of the competition between air defense and air penetration that we have identified. Our discussion of the hider-finder competition suggests that—far from becoming easier or cheaper—waging modern war will become more demanding, difficult, and expensive. Building on existing research, future works should explore these implications in greater depth.[214] Moreover, we have limited our focus to the current generation of drones, an inherent limitation given the rapid pace of technological change.[215] Unless technological advances will significantly alter or end the hider-finder competition between air defense and air penetration, there is little reason to believe that the future of war will be different from the past.[216] Yet, some practitioners and scholars have warned about such an epilogue.[217] Further research should investigate this topic.

212. "Is Latvia the Next NATO Nation to Order Bayraktar TB2 Drones?" *Defense World*, June 7, 2021, https://www.defenseworld.net/news/29744/Is_Latvia_the_Next_NATO_Nation_to_Order_Bayraktar_TB2_Drones_#.YNw7zhMzYmI. For a discussion, see Stein, "Say Hello to Turkey's Little Friend."
213. Borchert, Schütz, and Verbovszky, *Beware the Hype*, p. 23.
214. Erik Gartzke, "Blood and Robots: How Remotely Piloted Vehicles and Related Technologies Affect the Politics of Violence," *Journal of Strategic Studies*, Vol. 44, No. 7 (2021), pp. 983–1013, https://doi.org/10.1080/01402390.2019.1643329.
215. Calcara et al., *Will the Drone Always Get Through?*
216. For a discussion, see Biddle, *Military Power*, pp. 72–73.
217. Paul Scharre, *Robotics on the Battlefield Part II: The Coming Swarm* (Washington, D.C.: Center for a New American Security, 2014); and Robert Work, James A. Winnefeld Jr., and Stephanie O'Sullivan, "Steering in the Right Direction in the Military-Technical Revolution," *War on the Rocks*, March 23, 2021, https://warontherocks.com/2021/03/steering-in-the-right-direction-in-the-military-technical-revolution/.