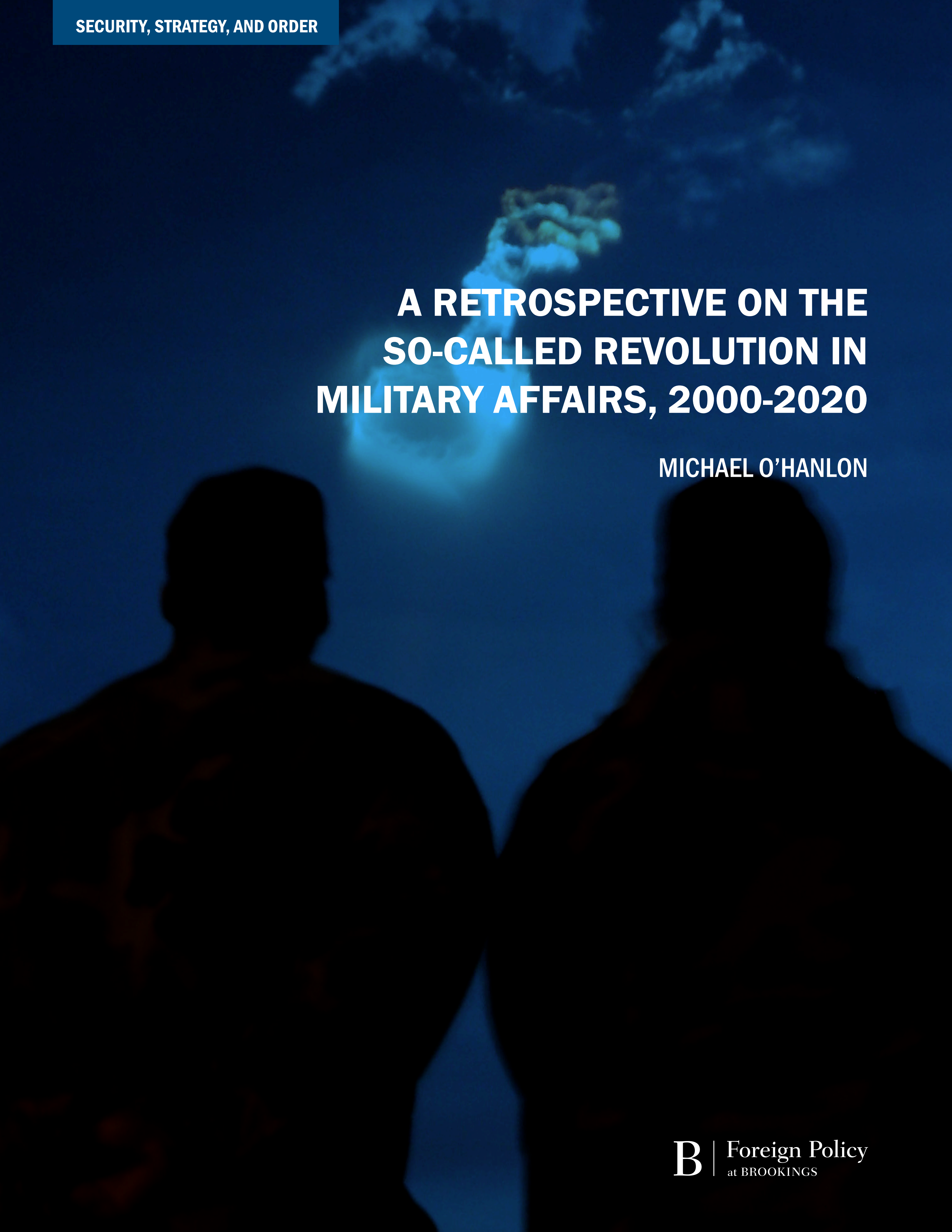

SECURITY, STRATEGY, AND ORDER

A RETROSPECTIVE ON THE SO-CALLED REVOLUTION IN MILITARY AFFAIRS, 2000-2020

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Foreign Policy
at BROOKINGS

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EXECUTIVE SUMMARY[1]

This paper revisits the debate that raged in American defense circles in the 1990s over whether a revolution in military affairs was imminent in the early parts of the 21st century. It also seeks to establish a benchmark, and reaffirm as well as refine a methodology, for forecasting future changes in military-related technologies by examining what has transpired in the first two decades of the 21st century. Taking this approach helps improve and validate the methodology that is employed in my forthcoming book, *The Senkaku Paradox: Risking Great Power War Over Small Stakes* (2019). A subsequent paper seeks to extrapolate a similar analysis out to 2040, gauging the potential for major breakthroughs in military technology and associated operational concepts over the next two decades. Such analysis is of critical importance for evaluating American and allied military and strategic options relevant to great-power war and deterrence in the years ahead.

The paper's category-by-category examination of military technology mirrors the approach that I employed in a book published in 2000, *Technological Change and the Future of Warfare* (though it really should have been entitled, *The So-Called Revolution in Military Affairs*, because I was largely challenging the then-popular notion that a military revolution of historic importance was afoot). Much of the research foundation of that book was the study of a list of 29 different types of technologies in an attempt to gauge which might undergo revolutionary change by 2020. Through a combination of basic concepts of physics, examination of the scientific and engineering literature on various types of technological research, and consultation with experts including at several of the nation's major weapons laboratories, I argued that in fact only two of the 29 were likely to experience truly revolutionary change. Those two were computer hardware and computer software. I predicted that another eight categories would likely witness high change—chemical sensors, biological sensors, radio communications, laser communications, robotics, radio-frequency weapons, nonlethal weapons, and biological weapons. The remaining 19 categories of key military technologies, many of them sensor

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[1] This paper draws from Michael E. O'Hanlon, *The Senkaku Paradox: Risking Great Power War Over Small Stakes* (Washington, DC: Brookings Institution Press, forthcoming 2019).

technologies or major components of weapons platforms like ground combat vehicles, aircraft, ships, and rockets, seemed likely to advance at only modest or moderate rates.[2]

As noted, to establish a baseline for predicting future change, I first revisit the taxonomy from the 2000 book here, attempting to "grade my own homework" with the 2000-2020 period now nearly over. With that as a baseline, I then attempt in a separate paper to look out from 2020 to 2040, in effect repeating the exercise with a methodology that has been time-tested—and also improved, in response to those areas of technology where my prognostications were less accurate.[3] As with the 2000 book, my assessments employ the same three gradations of anticipated technological innovation—revolutionary, high, and modest/moderate.

In very broad strokes, the findings of this paper are as follows. First, the relatively cautious assessment that I offered in the earlier book of where technological innovation would likely take us from 2000 through 2020 has been generally borne out. There has been a great deal of innovation since 2000, but it would be hard to describe most of it as revolutionary. That was the central argument of the 2000 book, and it would appear to be validated by the ensuing history.

Consider several key categories of military technology. The ages of space, stealth, and precision strike had already arrived by 2000; progress has surely continued since then, yet it has been progress mostly of degree rather than of kind. And tasks that were difficult at the turn of the century, even for very advanced militaries, remain generally very hard today, including missile defense, most dimensions of anti-submarine warfare, and most aspects of infantry combat.

Some things have changed a great deal—the use of remotely piloted aerial vehicles, armed and unarmed, for example. Other types of robotics have improved greatly; relatedly, miniaturized satellites have become much more widespread. But what is generally striking is that these have been in niche areas of military operations (important, yet niche areas just the same), and that they have generally not displaced the other kinds of systems that preceded them. By such standards, innovation has been better viewed as evolutionary rather than revolutionary.

To the extent that my earlier approach was not accurate, it was arguably in two areas: robotics and cybersecurity. The robotics revolution of the last 20 years has been in large part a result of progress in computers and other enabling technologies that were miniaturized and proliferated to a multitude of platforms. The synergies that resulted from miniaturization were more significant than I had appreciated by looking at individual areas of technology one by one. In addition, the incentives felt by the American military in particular were intensified by the post-9/11 experience. From the search for al-Qaida targets, to the discrete use of lethal military force from platforms that were more expendable and less politically visible than other options, to a number of other uses, drones and other robotics moved to the forefront of warfare.

And with extraordinarily improved computers, which I did expect, have come remarkable new vulnerabilities in cyberspace, which I did not adequately anticipate. Indeed, that may be the most consequential development of all between 2000 and 2020.

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[2] Michael E. O'Hanlon, *Technological Change and the Future of Warfare* (Washington, DC: Brookings Institution Press, 2000), 65.

[3] Michael E. O'Hanlon, "Forecasting Change in Military Technology, 2020-2040," (Washington, DC: Brookings Institution, forthcoming 2018).

My partial failures of foresight in these two realms of military technology and operations are instructive for designing any methodology that looks to the future. Importantly, it was most difficult to prognosticate about ways in which multiple technologies might be combined, or about ways in which military organizations might respond to new technological opportunities that required multi-step processes to reach their potential. In terms of robotics, military organizations responded with innovative and entrepreneurial acumen. That is perhaps because the needs for such capabilities were dramatized by the realities of war; lives could be saved, and prospects for success throughout much of the broader Middle East improved, with a serious program of weaponizing unmanned aerial vehicles (UAVs) and otherwise improving the capacities of robotics. Military organizations had major real-world incentives and life-or-death reasons to innovate.[4]

With computers, they did not—indeed, they carelessly allowed themselves to build Achilles' heels into their own systems, potentially making the performance of future weapons less dependable than past ones had been. In other words, they may even have set themselves back, though it is impossible to know for sure at this point, since we have not seen the kind of interstate warfare among near-peer competitors that would probably be needed to assess the hypothesis accurately. Those operating in the classified world may have a greater sense of the vulnerabilities and opportunities that the United States now faces due to cyber vulnerability, but even they cannot be sure. That is because cyber vulnerabilities are not static, they are always evolving in a game of measures and countermeasures, even faster than in other areas of military operations characterized by such dynamics such as electronic warfare. In addition, the ripple effects of any cyberattack often cannot be easily foreseen even when specific vulnerabilities are understood.

Looking forward, it is therefore possible that the rapid pace of computer innovation, which has led to much greater capacity for miniaturization and for robotics of many types, and also created major vulnerabilities in cyber domains together with looming opportunities in artificial intelligence, may make the next two decades somewhat more revolutionary than the last two. The dynamics in robotics and in cybersecurity discussed here may only intensify and extend into realms such as artificial intelligence. At least, an examination of the last 20 years would seem to suggest the potential for such an acceleration, particularly in light of the fact that multiple countries (most notably China, but also Russia) now have the resources to compete with Western nations in military procurement and innovation. That is the main implication of this paper's assessments of change in key areas of military technology.

THE 1990S DEBATE ABOUT A REVOLUTION IN MILITARY AFFAIRS

In the 1990s, a debate raged in the United States about whether a revolution in military affairs was happening. The question was, did contemporary changes in technology make possible radical changes in how militaries could organize, equip, and fight, rivaling for example the changes witnessed in the 1930s and 1940s when blitzkrieg, carrier warfare, amphibious assault operations, and finally nuclear weapons played crucial

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[4] For a related discussion of how strategic factors shape organizational behavior in regard to military innovation, see Barry R. Posen, *The Sources of Military Doctrine: France, Britain and Germany between the World Wars* (Ithaca, NY: Cornell University Press, 1984).

roles in World War II?[5] As evidenced by this historical reference, the debate was of far more than academic significance. A nation failing to profit from new opportunities in how war could be waged might not just squander new battlefield opportunities for its own military; it could also find itself enormously vulnerable to a country that did innovate in a revolutionary fashion. Such arguments were offered to assert, for example, that the United States should substantially reduce its overseas military presence, participation in peace operations, and combat force structure so as to be able to afford greater research, experimentation, prototyping, and new military weapons and formations.[6] Given that defense budgets of the time were roughly one-third less than today's, the opportunity costs of dramatically expanding and accelerating innovation would have been significant.[7]

How to determine the best options for the United States in this situation? There was of course no one right answer or provably superior course of action. Judgment was required on multiple dimensions. However, in the debate of the time, I took note of the fact that advocates of the Revolution in Military Affairs (RMA) hypothesis often cited Moore's Law, which notes that computing power tends to double every 18 to 24 months in the modern era, or become half as expensive as before over that time period, in a process of exponential progress. They tended to argue, as for example in the 1997 National Defense Panel, that many other areas of military technology besides computers were starting to enjoy rates of innovation of comparable magnitude and pace—in fields ranging from bioengineering, to rocketry, to ground combat vehicles. If true, it seemed compelling to argue that the United States needed to reassess its military priorities radically.

But this set of contentions also suggested an analytical path forward in attempting to assess just how urgently the United States should pursue radical defense transformation. By examining a number of specific areas of technology that would be crucial to any wholesale change in how the country might prepare for and wage war, one could perhaps develop a sense of how fast and how comprehensively military technology really was changing.

In some cases, a review of trends in military research and development could provide insight. For example, despite the claim of some that light-skinned ground combat vehicles traveling up to 200 km/h and surviving a hostile battlefield by virtue of their

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[5] See for example, Williamson Murray, "Thinking about Revolutions in Military Affairs," *Joint Forces Quarterly*, (Summer 1997): 69-76; Barry R. Posen, *The Sources of Military Doctrine*, 7-80; Stephen Peter Rosen, *Winning the Next War: Innovation and the Modern Military* (Ithaca, NY: Cornell University Press, 1991), 13-100; and Max Boot, *War Made New: Technology, Warfare, and the Course of History, 1500 to Today* (New York: Gotham Books, 2006).

[6] See James R. Blaker, "The American RMA Force: An Alternative to the QDR," *Strategic Review* 25, (Summer 1997): 21-30; and "Transforming Defense: National Security in the 21st Century" (Arlington, VA: National Defense Panel, 1997).

[7] See for example, Andrew F. Krepinevich, "Cavalry to Computer: The Pattern of Military Revolutions," *The National Interest*, September 1, 1994, http://nationalinterest.org/article/cavalry-to-computer-the-pattern-of-military-revolutions-848; Martin C. Libicki, "DBK and Its Consequences," in *Dominant Battlespace Knowledge*, eds. Stuart E. Johnson and Martin C. Libicki(Washington, DC: National Defense University Press, 1996), 23-49; Statement of General Ronald R. Fogleman, Chief of Staff, U.S. Air Force, before the House National Security Committee, 105th Congress, 1st session, May 22, 1997; Defense Science Board 1996 Summer Study Task Force, *Tactics and Technology for 21st Century Military Superiority, vol. 1* (Washington, DC: Department of Defense, 1996), pp. S-1 through S-4; Alvin Toffler and Heidi Toffler, *War and Anti-War: Survival at the Dawn of the 21st Century* (Boston: Little, Brown, 1993); Admiral Arthur K. Cebrowski and John J. Garstka, "Network-Centric Warfare: Its Origins and Future," *Proceedings* 124, no. 1 (1998): 28-35; Robert H. Scales, Jr., "Cycles of War: Speed of Maneuver Will Be the Essential Ingredient of an Information-Age Army," *Armed Forces Journal International* 134, (July 1997); and Zalmay Khalilzad and David Shlapak with Ann Flanagan, "Overview of the Future Security Environment," in *Sources of Conflict in the 21st Century*, eds. Zalmay Khalilzad and Ian O. Lesser (Santa Monica, CA: RAND, 1998), 30-36.

sensor networks and maneuverability would replace Abrams tanks and other existing heavy equipment, there seemed little about trends in engines, armor, or other key constituent technologies that could help such a vision come to pass. In other cases, the unchanging laws of physics counseled caution. For example, the claims of some that somehow the “oceans would become transparent” to new sensor technologies conflicted directly with the fact that no wavelength of electromagnetic radiation tends to penetrate more than 100 to 200 meters underwater (at most), as well as the fact that sonar technology appears largely mature.

In short, there were ample reasons for skepticism that any broad-based RMA was at hand. These analyses did not prove the case definitively, because in theory, a few areas of radical technological change could themselves create an adequate foundation for linking existing weapons technologies together in new ways that created revolutionary effects. But a sober examination of the various key areas of technology would nonetheless help provide a good benchmark about the likely potential of new capabilities. After all, the World War II revolutions depended in large part on radically new capabilities in areas of airpower (on land bases and carriers), communications systems, submarine forces, and ultimately nuclear weapons. Previous revolutions tended to coincide with comparably seismic changes in the technology landscape, such as armored ships driven with propellers, railroads for movement of huge armies, and telegraphs for rapid communications in the field. To put it somewhat simplistically, it seemed reasonable to doubt if a new Windows operating system on a faster type of computer could themselves largely drive a revolution. As noted above, computer hardware and computer software were the only two areas of major military-related technology where my analysis in 2000 led me to forecast revolutionary change.

ASSESSING THE REVOLUTION IN MILITARY AFFAIRS HYPOTHESIS, 2000-2020

How have things actually turned out? In order to help understand where trends in technology have arguably been, and to gain at least some insight into how feasible it really might be to project future technology trends a score of years into the future, it is worth first comparing my predictions with what has actually transpired. Doing so can help validate the methodology of trying to peer into the future by examining a number of specific technology areas or categories, and can perhaps also help improve the methodology by understanding where (and why) my predictions diverged from the actual course of events.

My basic premise is that 20 years is long enough to represent a true extrapolation into the future, but short enough that existing trends in laboratory research can help us understand where we will be after that timeframe. Since many defense systems take a couple decades to develop, it should not be an overly daunting task to gauge how the world might look 20 years or so from now. It was this view, rather than any belief in my profound understanding of physics and engineering, or any possession of a crystal ball, that led me to attempt the prognostication back at the turn of the century.

Consider what has actually happened since then, with the 29 constituent technologies that I identified and organized into four major categories: sensors; computers and communications; projectiles, propulsion, and platforms; and, finally, “other weapons.” In each case, I attempted to project how much technology both available and deployable by the year 2020 might produce major changes in warfare.

FIGURE 1: ESTIMATED ADVANCES IN KEY DEPLOYABLE TECHNOLOGIES, 2000-2020

	Moderate	High	Revolutionary	Revised, 2018
Sensors				
Chemical sensors		X		**Moderate**
Biological sensors		X		**Moderate**
Optical, infrared, and UV sensors	X			No change
Radar and radio sensors	X			**High**
Sound, sonar, and motion sensors	X			No change
Magnetic detection	X			No change
Particle beams (as sensors)	X			No change
Computers and communications				
Computer hardware			X	No change
Computer software			X	No change
Radio communications		X		**Moderate**
Laser communications		X		**Moderate**
Projectiles, propulsion, and platforms				
Robotics		X		**Revolutionary**
Missiles	X			**High**
Explosives	X			No change
Fuels	X			No change
Jet engines	X			No change
Internal-combustion engines	X			No change
Rockets	X			No change
Ships	X			No change
Armor	X			No change
Stealth	X			No change
Other weapons				
Radio-frequency weapons		X		**Moderate**
Nonlethal weapons		X		**Moderate**
Biological weapons		X		**Moderate**
Other weapons of mass destruction	X			No change
Particle beams (as weapons)	X			No change
Electric guns	X			No change
Lasers	X			No change
Long-range kinetic energy weapons	X			No change

Note: 1) The terms moderate, high and revolutionary are subjective and somewhat imprecise. In general terms, technologies showing moderate advances might improve their performance by a few percent or at most a couple of tens of percent—in terms of speed, range, lethality, or other defining characteristics—between 2020 and 2040. Those experiencing high advances will be able to accomplish taskes on the battlefield far better than before—perhaps by 50 to 100 percent, to the extent improved performance can be so quantified. Finally, technology areas in which revolutionary advances occur will be able to accomplish important battlefield tasks that they cannot now even attempt. 2) Taken from Michael E. O'Hanlon, *Technological Change and the Future of Warfare* (Brookings Institution Press, 2000).

Sensors

In my original taxonomy, I identified seven types of sensors based on what they were looking for and what physical phenomena or processes they relied upon in their searches. Three categories—radar and radio; optical, infrared, and ultraviolet sensors; and magnetic detectors—make use of one type or another of electromagnetic radiation. Another type involves sound and sonar. Particle beams are a fifth category. Biological sensors and chemical sensors round out the list.

New concepts were being explored for biological and chemical sensors at the turn of the century, even before the 9/11 attacks (and ensuing anthrax attacks as well) gave rise to a greater sense of urgency about improving systems that were often viewed as slow to work or quite limited in the range of agents they could detect. Laser systems that might remotely identify the molecules in a given cloud of gas, or biological detectors that were potentially able to match DNA against detailed databases, seemed to offer hope for substantial improvement. As such, I rated those two categories of sensors as being poised for a high rate of change. As for everything else, it seemed wise to advise very modest expectations. Sensors involving passive detection of electromagnetic radiation were constrained largely by the fact that such radiation could not easily traverse many common geographic features of the modern battlefield. Physics limits the transit of all electromagnetic radiation through water, for example, with only blue-green visible light realistically having a chance to penetrate further than about 100 meters. Metals, too, block radiation. Sonar technology had entered a largely mature phase with little seeming prospect of major improvement. Particle beams, requiring active energy that needed to be generated and then directed toward a possible target, were (and are) generally limited in potential by power considerations. Little about the state of research on such systems (like neutron generators) suggested imminent big breakthroughs in systems that could easily be deployed to a battlefield.

If anything, I would conclude that my initial prognostications on sensors were too bullish on the prospects for progress. Chemical and biological sensors have not advanced at a pace that one could realistically describe as high or rapid. Deployable detectors are still focused for the most part on one agent or pathogen at a time and are often unwieldy and slow. As for the other categories of sensors, sonars indeed have remained in a fairly plateaued state, with little change, for example, in the anti-submarine warfare mission (submarines are probably becoming quieter more quickly than sonar is able to improve sensitivity). Particle beams as sensors are still a glean in the eye of futurists, except for very close-in applications at specific locations (such as airport security sites, or in the short-range hunt for nuclear materials). Nothing about physics has, or can, change in a way that makes radio, infrared radiation, visible light, or ultraviolet light able to penetrate objects that they could not reach deeply into before.

These verdicts can be backed up with empirical observations of which systems the U.S. armed forces (and to a lesser extent, the Department of Homeland Security, or DHS, and other agencies) now deploy as sensors for various surveillance or warfighting purposes. New models may have emerged over the past two decades, but new phenomenologies generally have not. Capabilities have gradually improved and evolved; they have not changed dramatically. For example, the chemical weapons detection system around which the Department of Defense's (DoD) 2017 report on chemical and biological threats largely centers its attention, the Joint Chemical Agent Detector, is based on technology developed at the turn of the century.[8] Detectors that might, for example, find more trace concentrations, providing greater lead times when warning of dangerous levels of an agent, or detect chemical agents or biological pathogens remotely through laser spectroscopy or other such methods of remote interrogation, are not yet the predominant technologies in the field.[9]

DHS is prototyping a two-tier biological detection sensor system but it will still take up to 15 minutes to detect and identify a relatively narrow range of potential pathogens at close-in range. That is not dramatically different from where technologies stood two decades ago, even if there has been considerable effort in making systems somewhat more deployable and user-friendly.[10] For example, the basic BioWatch technology on which current systems are based largely reflects modifications to technology and concepts first deployed in 2003, shortly after the anthrax attacks that followed 9/11.[11] The so-called Next Generation Diagnostics System is described in Army literature as better than predecessors at detecting multiple agents simultaneously, not as a radically new capability.[12] Some new ideas are being pursued. For example, Lawrence Livermore National Laboratory has created the Lawrence Livermore Microbial Detection Array that examines DNA directly (without requiring cultures) and searches for a wide range of bacteria, viruses, and fungi. However, this technology to date has been used for very specialized applications and is not at the basis of current DHS or DoD deployable systems; it also requires 24 hours to detect a pathogen.[13]

Sonar is improving gradually through better signals processing capabilities and through expanded use of robotics to proliferate sensors, to be sure.[14] But these changes are evolutionary, and the basic systems in service are changing little. For example, one contractor whose "CAPTAS" sonar system was chosen for the Navy's newest surface combatant, the Littoral Combat Ship, describes the technology as "very mature" and notes that its first variant was deployed in the early 1990s.[15] Detection ranges for prominent active sonars (those that emit their own signal, then listen for the echo)

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[8] Charles E. Laljer, "Joint Chemical Agent Detector: The Future of Chemical Agent Detection," (San Antonio, TX: MITRE Corporation, March 2000), https://www.mitre.org/publications/technical-papers/joint-chemical-agent-detector-jcad-the-future-of-chemical-agent-detection; DoD Chemical and Biological Defense Office, "2017 Annual Report to Congress," (Washington, DC: Department of Defense, 2017), 5, https://fas.org/irp/threat/cbw/cbd-2017.pdf; and Rodi Sferopoulos, "A Review of Chemical Warfare Agent Detector Technologies and Commercial-off-the-Shelf Items," (Melbourne: Australian Department of Defence Science and Technology Organization, 2009), 10, http://www.dtic.mil/dtic/tr/fulltext/u2/a502856.pdf.

[9] Joey Cheng, "Small, Deep-UV Lasers Could Detect Biological and Chemical Agents on the Battlefield," *Defense Systems*, March 24, 2014, https://defensesystems.com/articles/2014/03/24/darpa-luster-chem-bio-detection.aspx.

[10] Science and Technology Directorate, "Detect to Protect Bio-Aerosol Detection Systems," (Washington, DC, Department of Homeland Security, April 2016), https://www.dhs.gov/sites/default/files/publications/Detect%20to%20Protect%20Bio-Aerosol%20Detection%20Systems_0.pdf.

[11] Reginald Brothers and Kathryn H. Brinsfield, "Joint Testimony of Reginald Brothers, PhD Under Secretary for Science and Technology U.S. Department of Homeland Security And Kathryn H. Brinsfield, MD, MPH Assistant Secretary for Health Affairs and Chief Medical Officer U.S. Department of Homeland Security," (testimony, U.S. House of Representatives Committee on Homeland Security Subcommittee on Emergency Preparedness, Response, and Communications, Washington, DC, February 11, 2016), http://docs.house.gov/meetings/HM/HM12/20160211/104326/HMTG-114-HM12-Wstate-BrinsfieldK-20160211.pdf.

[12] Chemical, Biological, Radiological, and Nuclear Information Resource Center, "Next-Generation Diagnostics System, Increment 1," (Washington, DC, U.S. Army, July 27, 2017), https://jacks.jpeocbd.army.mil/Public/FactSheetProvider.ashx?productId=594.

[13] Stephen Wampler, "LLNL Biodetection System Bound for Space," *Lawrence Livermore National Laboratory*, April 28, 2016, https://www.llnl.gov/news/llnl-biodetection-system-bound-space.

[14] John Keller, "New Era Dawns in ASW as Manned and Unmanned Submarines Team for Bistatic Sonar," *Military and Aerospace Electronics*, October 24, 2017, http://www.militaryaerospace.com/articles/print/volume-28/issue-10/news/news/new-era-dawns-in-asw-as-manned-and-unmanned-submarines-team-for-bistatic-sonar.html.

[15] James Gray, "CAPTAS Variable Depth Sonar," *Leonardo DRS*, 2017, http://www.leonardodrs.com/products-and-services/captas-anti-submarine-warfare.

are still often measured in the single-digit kilometers, as in past eras.[16] Even relatively simple submarines have a decent chance of approaching ships equipped with modern sonar, under certain operating and oceanic conditions—such as the case in 2006 when a Chinese Type 039 Song-Class submarine surfaced, previously undetected, within about 5 miles of a U.S. aircraft carrier.[17]

Particle beams, used either as sensors or weapons, include free electron lasers, neutron beams, and alpha-particle beams. They remain technologically possible but logistically impractical for most military purposes—a verdict not unlike what might have been rendered two decades ago. They are simply too big, unwieldy, and expensive for most potential applications, except typically at fixed or otherwise discrete sites.[18] To be sure, innovations have occurred in specific ways. For example, some newer detection systems may employ plastic materials as sensors, thereby making it easier to deploy the sensors more widely.[19] But the battlefield applications of such advances remain circumscribed, largely because ranges are quite limited.

Lasers as sensors have progressed somewhat more. For example, they are in use with a number of artillery systems now (though the original U.S. type of laser-guided artillery, the Copperhead, predated the 21st century).[20] Another example is with shallow-water anti-submarine warfare. But even here progress is slow—and the properties of the oceans limit severely the depths to which such sensors, as well as laser communications systems like a Defense Advanced Research Projects Agency (DARPA) concept called TRITON, can credibly operate.[21] What is perhaps most notable about laser sensor technology over the past two decades is its continued proliferation, more than major advances in fundamental capabilities. For example, even the Taliban in Afghanistan

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[16] Kongsberg Maritime AS, “Anti-Submarine Warfare Sonar: Variable Depth Sonar ST2400,” (Horten, Norway, Kongsberg, 2017), https://www.km.kongsberg.com/ks/web/nokbg0397.nsf/AllWeb/E3A077B4603D7228C1256C390041B9D8/$file/855-1644175af_ST2400_product_specification_lr.pdf?OpenElement.

[17] James Holmes, “North Korea Could Sink a U.S. Aircraft Carrier,” *The National Interest*, January 5, 2018, http://www.nationalinterest.org/blog/the-buzz/north-korea-could-sink-us-aircraft-carrier-23953.

[18] See for example, “Neutron Beam Applications,” Massachusetts Institute of Technology Nuclear Reactor Laboratory, https://nrl.mit.edu/research/neutron-beam; Walter Henning and Charles Shank, “Accelerators for America’s Future,” (Washington, DC: Department of Energy, 2010), https://science.energy.gov/~/media/hep/pdf/files/pdfs/Accel_for_Americas_Future_final_report.pdf; Ben Dotson, “How Particle Accelerators Work,” *Department of Energy*, June 18, 2014, https://energy.gov/articles/how-particle-accelerators-work; and D. Ridikas and V. Inozemtsev, “Use of Neutron Beams for Materials Research Relevant to the Nuclear Energy Sector,” (Vienna: International Atomic Energy Agency, 2015), http://www-pub.iaea.org/MTCD/Publications/PDF/TE-1773_web.pdf.

[19] Stephen P. Wampler, “Lawrence Livermore Laboratory Team Achieves Breakthrough Detecting Nuclear Materials,” *Lawrence Livermore National Laboratory*, January 11, 2012, https://www.llnl.gov/news/lawrence-livermore-laboratory-team-achieves-breakthrough-detecting-nuclear-materials; and Arden D. Dougan et al., “New and Novel Nondestructive Neutron and Gamma-Ray Technologies Applied to Safeguards,” (Livermore, CA: Lawrence Livermore National Laboratory, 2007), http://www-pub.iaea.org/mtcd/meetings/PDFplus/2007/cn1073/Presentations/4A.2%20Pres_%20Dougan%20-%20New%20and%20Novel%20Nondestructive%20Neutron%20and%20Gamma-Ray%20Technologies%20Applied%20to%20Sa.pdf.

[20] Christopher F. Foss, “Smart ammo: precision-guided munitions for field,” *Jane’s Defence Weekly*, 2015, http://www.janes360.com/images/assets/423/54423/precision-guided_munitions_for_field_artillery.pdf; and Robert Sherman, “M712 Copperhead,” *Federation of American Scientists*, January 21, 1999, https://fas.org/man/dod-101/sys/land/m712.htm.

[21] Graham Templeton, “A Deeper Look into Lasers, Particle Beams, and the Future of War,” *Extreme Tech*, April 25, 2013, https://www.extremetech.com/extreme/153585-a-deeper-look-into-lasers-particle-beams-and-the-future-of-war; Weilin Hou, “Blue-Green Laser Communications Critical Technologies for Anti-Submarine Warfare and Network Centric Operations,” *International Defence, Security, and Technology*, September 8, 2017, http://idstch.com/home5/international-defence-security-and-technology/technology/photonics/blue-green-laser-communications-and-lidar-critical-technologies-for-anti-submarine-warfare-and-network-centric-operations; and Peter Coates, “LIDAR: An Anti-Submarine Warfare Sensor,” *Intelligence and Submarine Matters*, January 16, 2014, http://gentleseas.blogspot.com/2014/01/lidar-anti-submarine-warfare-sensor.html.

have reportedly made frequent use of laser targeting with rifles (as well as night-vision technology) in recent years.[22]

Infrared detectors have continued to improve and proliferate too. New systems are more sensitive, cheaper, smaller, more portable, and thus more widely usable than earlier generations. Today's detector focal plane array (FPA) systems are up to 100 times more sensitive, as measured in terms of pixels per array, compared to 20 years ago (and a million times more sensitive than a half century ago). Whether the developments of the last 20 years amount to revolutionary change, given what had already transpired just before, or a rapid evolution/improvement of existing concepts can be debated.[23]

Despite the progress, the basic challenge in regard to infrared, ultraviolet, and visible light employed as sensors remains, and will always remain, physics. There was no change in this basic situation since 2000; indeed, there *could not* have been. Despite the extremely impressive technologies that now exist that exploit these kinds of electromagnetic radiation, the simple fact is that they are rapidly attenuated or blocked by a number of prevalent materials on Earth. Water is perhaps the most significant. That means that most soil is also difficult to penetrate very far with any kind of sensor employing such radiation. (Ultraviolet light, gamma rays, and x-rays fare worse than visible light, by the way. Radar is also severely compromised by water, though extremely low frequency [ELF] waves are a partial exception and can penetrate nearly a factor of 10 further than visible light.)[24] Metal is another fairly unyielding barrier to electromagnetic radiation. Leaves, thin wood, and other materials with some water content may allow a certain modest transmission but even here, there is no getting around the physics. As such, radiation near or within the visible spectrum is largely limited to direct line-of-sight purposes through the atmosphere or space (and even the atmosphere can of course be less than transparent, especially when high in humidity).[25]

Still, there have been important areas of progress in these latter sensor technologies. For example, the capacity to use satellite-borne radar to carry out ground moving-target indication (GMTI) has advanced considerably, due largely to improvements in algorithms for identifying the moving objects in a sea of radar returns.[26]

Computers, robotics, and communications

In 2000, I predicted that advances over the ensuing 20 years would create revolutionary progress in computer software and hardware. I predicted that innovation would be high, or fast, in robotics, largely because of improvements in computers. And in regard to radio and laser communications, I also forecast high/fast progress, the intermediate category that I employed to gauge the pace of change.

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[22] Taimoor Shah and Rod Nordland, "Taliban Kill Dozens of Afghan Police Officers in 2nd Night of Attacks," *The New York Times*, November 14, 2017, https://www.nytimes.com/2017/11/14/world/asia/afghanistan-taliban-attack-police.html.

[23] A. Rogalski, "History of Infrared Detectors," *Opto-Electronics Review* 20, no. 3 (2012): 297-298, 305-306, https://pdfs.semanticscholar.org/7b0a/f5463bc3be37a1b4649a6c80e56b350b94ec.pdf; and Maxtech International, "New Market Research On The World Market For Military Infrared Imaging Detectors And Systems," *Cision PR Newswire*, January 15, 2015, https://www.prnewswire.com/news-releases/new-market-research-on-the-world-market-for-military-infrared-imaging-detectors-and-systems-vol-irw-m-2015-edition-by-maxtech-international-inc-300016384.html.

[24] J.D. Jackson, *Classical Electrodynamics*, 2nd ed. (New York: John Wiley and Sons, 1975), 290-292.

[25] Duncan Brown, "Joint Staff J-7 Sponsored Science, Technology, and Engineering Futures Seminar," (Laurel, MD: Johns Hopkins University Applied Physics Laboratory, July 2014), 15.

[26] Joseph Post and Michael Bennett, *Alternatives for Military Space Radar* (Washington, DC: Congressional Budget Office, 2007), 1-10.

In these areas of communications, I may have been too bullish. Laser communications through fiber optic cables is prevalent, to be sure, but it already was in 2000. In mobile settings on the battlefield, lasers are not yet in wide use for purposes of exchanging information or messages.[27] Frequency-hopping radios aided by better computing power have improved, but probably not radically. Meanwhile, growing worries about cyber vulnerabilities have restrained some of the enthusiasm that might have existed around enhanced radio communications, as has reinvigorated Russian and Chinese interest in electronic warfare. Many "legacy" systems such as the Single-Channel Ground and Airborne Radio System (SINCGARS) remain in common use today.[28]

On computers, however, it seems fair to conclude that progress has continued to be revolutionary so far in the 21st century. In terms of hardware, "Moore's Law" has continued to apply, more or less, just as it had since the pattern of progress was coined by Gordon Moore in 1965. It posits that the number of transistors that can be placed on a single computer chip will double every two years—corresponding to a rough doubling in computer power as well. The pace of change has slowed modestly since the latter decades of the 20th century, but has remained quite impressive at least to date. Around 1970, several thousand transistors could be built onto a given chip; by 2000 the figure was roughly 10 million, and by 2015 it exceeded 1 billion.[29]

With this progress has come vastly greater computing power, much lower cost per unit of computing power—and, in the 21st century to date, what might be called the iPhone, Google, and Facebook revolutions (among other things). As new software, applications, and concepts for using mobile and inexpensive computing power have proliferated, radically different things have become possible in warfare as well. Robotics and automated aircraft have become far more capable, as small processing units can guide them. Hit-to-kill missile defense interceptors, such as the Terminal High-Altitude Area Defense (THAAD) and Standard Missile systems, can maneuver well enough to collide with an incoming threat. Mortars can steer themselves to target via GPS signals. The list goes on.[30]

With the progress in computers has come far greater cyber vulnerability. This development may, in warfighting circumstances, be even more significant than the positive attributes of computers. By effectively building Achilles' heels into everything they operate, modern militaries have created huge opportunities for their potential enemies. The fact that everyone is vulnerable, in some sense, is no guarantee of protection. A country figuring out how to integrate cyberattack plans that are temporarily crippling into an integrated

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[27] George Leopold, "Laser Comms from Space Gets Another Test," *Defense Systems*, February 17, 2017, https://defensesystems.com/articles/2017/02/17/spacelaser.aspx; and Sydney J. Freedberg, Jr., "Say It With Lasers: $45 Million DoD Prize for Optical Coms," *Breaking Defense*, May 30, 2017, https://breakingdefense.com/2017/05/say-it-with-lasers-45m-dod-prize-for-optical-coms.

[28] U.S. Army, "Techniques for Tactical Radio Operations," (Fort Belvoir, VA: U.S. Army Publishing Directorate, January 2016), http://www.apd.army.mil/epubs/DR_pubs/DR_a/pdf/ARN3871_ATP%206-02.53%20FINAL%20WEB.pdf; David Axe, "Failure to Communicate: Inside the Army's Doomed Quest for the 'Perfect' Radio," *Center for Public Integrity*, May 19, 2014, https://www.publicintegrity.org/2012/01/10/7816/failure-communicate-inside-armys-doomed-quest-perfect-radio; and James Hasik, "Avoiding Despair About Military Radio Communications Is the First Step Towards Robust Solutions," *Real Clear Defense*, July 24, 2017, https://www.realcleardefense.com/articles/2017/07/24/avoiding_despair_about_military_radio_communications_is_the_first_step_towards_robust_solutions_111884.html.

[29] M. Mitchell Waldrop, "The Chips are Down for Moore's Law," *Nature*, February 9, 2016, http://www.nature.com/news/the-chips-are-down-for-moore-s-law-1.19338.

[30] See for example, Audra Calloway, "Army Developing Laser-Guided, Precision Mortar," *U.S. Army*, March 3, 2017, https://www.army.mil/article/183491/army_developing_laser_guided_precision_mortar.

operational concept may, even if still vulnerable to reprisal itself, be able to achieve dramatic success in the opening (and perhaps decisive) phases of a war.[31]

A retired high-ranking Army logistician recently described the evolution of the logistics enterprise over the course of recent decades, to the effect of: "In Operation Desert Storm in 1990-91, we didn't know where anything was half the time; we lost things in shipping as a matter of course. By Operation Iraqi Freedom in 2003, we were much better. But in the future, we may be much worse, because the enemy may return us to the dark ages through cyberattack."[32] A Defense Science Board study in early 2017 asserted that virtually no major U.S. weapon system had cyber systems that could be confidently vouched for.[33] An earlier 2013 Defense Science Board study put it even more dramatically:

> "The benefits to an attacker using cyber exploits are potentially spectacular. Should the United States find itself in a full-scale conflict with a peer adversary, attacks would be expected to include denial of service, data corruption, supply chain corruption, traitorous insiders, kinetic and related non-kinetic attacks at all altitudes from underwater to space. U.S. guns, missiles, and bombs may not fire, or may be directed against our own troops. Resupply, including food, water, ammunition, and fuel may not arrive when or where needed. Military commanders may rapidly lose trust in the information and ability to control U.S. systems and forces."[34]

This assessment of cyber vulnerability compounds the ongoing, indeed worsening, vulnerability of space assets. To be sure, the proliferation of satellites, including smaller systems, mitigates the vulnerability of certain types of large satellites, by providing backups for some purposes like low-resolution Earth imaging and communications. But the prevalence of microsatellites also amounts to the proliferation of potential anti-satellite devices. On balance, former Under Secretary of Defense James Miller and Richard Fontaine put it well in 2017: "… space may be a classically unstable domain in that it appears highly offense-dominant under current technological and deployment conditions."[35]

Projectiles, propulsion, and platforms

Lumping together missiles, rockets, explosives, fuels, jet engines, internal combustion engines, ships, armor, and stealth into a broad category involving major weapons systems and the mechanisms that moved them, my predictions back in 2000 were that such platform-centric technologies would continue to improve but only at a moderate pace. In other words, I predicted the slowest pace of the three possible measures of progress that my taxonomy allowed.

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[31] Not quite what I am describing here, but a useful evocative example of this kind of scenario nonetheless, is the fictional account developed in P.W. Singer and August Cole, *Ghost Fleet* (New York: Houghton Mifflin Harcourt, 2015).

[32] Conversation with unnamed retired general, Princeton University, Princeton, NJ, April 5, 2016.

[33] Defense Science Board, "Task Force on Cyber Deterrence," (Washington, DC: Department of Defense, February 2017), https://www.acq.osd.mil/dsb/reports/2010s/DSB-CyberDeterrenceReport_02-28-17_Final.pdf.

[34] Defense Science Board, "Resilient Military Systems and the Advanced Cyber Threat," (Washington, DC: Department of Defense, January 2013), 5, available at http://www.dtic.mil/get-tr-doc/pdf?AD=ADA569975.

[35] James N. Miller, Jr. and Richard Fontaine, "A New Era in U.S.-Russian Strategic Stability," (Washington, DC: Center for a New American Security, September 2017), 18, https://www.cnas.org/publications/reports/a-new-era-in-u-s-russian-strategic-stability.

My predictions were generally correct, I believe, though in regard to major weapons platforms it is almost too grandiose to claim that I was offering "predictions" per se. Many if not most of the new platforms dominating weapons inventories in 2020 were already being researched and quite often prototyped back in 2000. Prominent examples include the F-35 fighter, the Virginia-Class submarine, the Gerald Ford aircraft carrier, and Standard Missile systems. Twenty years is within the duration of the innovation cycle for most large platforms. Even the exceptions may prove the rule. For example, the so-called mine-resistant ambush-protected vehicle, or MRAP, may have been designed and built quickly, as a response to the wars of the early 21st century, but it tended to center on technologies that had been around for quite a while and that were hardly cutting-edge in their main character.

Perhaps the long time required to design, test, build, and field new weapons platforms is in part a flaw of the U.S. weapons acquisition system. However, it is not clear that platform technology is advancing so fast as to normally require a more supple and fast-moving process. As former Deputy Secretary of Defense William Lynn argued in a forum at Brookings in 2015, the Department of Defense may get a mediocre grade for "anything touched by Moore's Law," given that electronics and computers are advancing so fast, but it arguably does pretty well in regard to bending metal and building vehicles, ships, and planes.[36]

A few snapshots of data can help paint a broad mosaic of the overall trend lines. Take for example the internal combustion engine. In passenger vehicles, its efficiency as measured in horsepower per volume of engine size has improved roughly a third this century so far, roughly the same pace per decade as in the latter quarter of the 20th century. (In most engines, efficiency in converting thermal energy into mechanical energy is 20 to 30 percent, or about half the theoretical maximum, with diesel engines more efficient than gasoline models.)[37] Tank engines have progressed at similar proportionate rates.[38] In other words, progress has been steady but gradual. A 2014 paper by a well-known expert in the field projected progress of 2 to 5 percent in a dozen or so major elements of the functioning of an engine—hardly insignificant, especially if combined together, but not revolutionary in character either.[39]

Jet engines have evolved continuously as well, but of course, they have also been around a long time. Modern fighter engines might typically have twice the thrust of those of a generation ago (comparing, for example, the F135 engine for the F-35 to the F100-PW-220 for the F-16).[40] Looked at another way, in terms of fuel efficiency, jet engines improved dramatically in the latter half of the 20th century, cutting the amount of fuel required for a given amount of payload-distance by two-thirds (with most of that progress

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[36] Proceedings of a panel discussion at Brookings, "Acquisition Reform: Increasing Competition, Cutting Costs, and Out-Innovating the Enemy," Brookings Institution, April 13, 2015, https://www.brookings.edu/events/acquisition-reform-increasing-competition-cutting-costs-and-out-innovating-the-enemy.

[37] Gurpreet Singh, "Overview of the DOE Advanced Combustion Energy R&D Program," (Washington, DC: Department of Energy, June 16, 2014), https://www.energy.gov/sites/prod/files/2014/09/f18/ace_rd_overview_2014_amr.pdf; Jerald A. Caton, "Maximum Efficiencies for Internal Combustion Engines: Thermodynamic Limitations," *International Journal of Engine Research*, (October 2017), http://journals.sagepub.com/doi/pdf/10.1177/1468087417737700.

[38] Alec Wahlman and Brian M. Drinkwine, "The M1 Abrams: Today and Tomorrow," *Military Review*, November/December 2014, http://www.armyupress.army.mil/Portals/7/military-review/Archives/English/MilitaryReview_20141231_art006.pdf.

[39] John B. Heywood, "Improving Engine Efficiency and Fuels: An Overview," (conference presentation, Baltimore, MD, February 2014), https://crcao.org/workshops/2014AFEE/Final%20Presentations/Day%201%20Intro%20Presentations/I1-1%20Heywood,%20John%20-%20Presentation%20[Compatibility%20Mode].pdf.

[40] Pratt and Whitney, "F135 Engine: Fast Facts," Pratt and Whitney, May 2016, available at http://pdf.aeroexpo.online/pdf/pratt-whitney/f135-engine/170325-4930.html.

achieved by 1980). This century, the additional reduction has been in the vicinity of a third.[41] Still, this progress in engine technology is better seen as more evolutionary than revolutionary. The point is driven home, for example, when one considers that the F-22 Raptor, which, just like the F-16 Fighting Falcon a generation before it, is a "Mach 2 class" aircraft. To be sure, the performance of the Raptor is much better than that of the Falcon in many ways, including its ability to reach supersonic speeds without using afterburners. But the fact remains that their maximum speed remains in the same general range.[42]

Fuels have effectively remained the same. In fact, the Air Force arguably accepted a slightly lower standard in terms of fuel performance, going from JP-8 to Jet A several years ago in order to allow access to the broader commercial jet fuel market and thereby save money.[43] Similarly, explosive materials are not changing much. Chemicals such as HXM and CL-20 have been around for decades; attempts at improvement are at the margin of performance, seeking enhancements of perhaps several percent in standard indicators like detonation velocity.[44]

Armor for heavy combat vehicles has continued to improve. But most of the main innovations in widespread use today—depleted uranium armor, explosive-reactive armor, and ceramic materials—were developed in the late 20th century. Today's newer concepts involve ideas such as laser defenses and active defenses, which could be important as they improve—but which are not about providing armored protection per se.[45]

As for large rockets, the pace of change here has been quite modest. Aspirations in the 1990s to find means of putting payloads cheaply into Earth orbit have simply not been met. Costs per pound of payload have remained similar to what they have been since the days of the Saturn rockets and Apollo program.[46] That may change soon, as discussed in my other concurrent paper, "Forecasting Change in Military Technology, 2020-2040."[47] But to date, it has not.

Where there has been significant progress, it has been in making the payloads themselves smaller through the use of miniaturized satellites for many purposes. In

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[41] Jean-Paul Rodrigue, "Trends in Fuel Efficiency, Selected Passenger Jets," Hofstra University, 2017, https://people.hofstra.edu/geotrans/eng/ch3en/conc3en/aircraftenergyefficiency.html; and Thomas K. Grose, "Reshaping Flight for Fuel Efficiency: Five Technologies on the Runway," *National Geographic*, April 23, 2013, https://news.nationalgeographic.com/news/energy/2013/04/130423-reshaping-flight-for-fuel-efficiency.

[42] See "F-16 Fighting Falcon," Lockheed Martin, https://www.lockheedmartin.com/en-us/products/f-16.html; and "F-22 Raptor," Lockheed Martin, https://www.lockheedmartin.com/us/products/f22/f-22-specifications.

[43] Jared Anderson, "U.S. Air Force Completes Jet Fuel Conversion; Impacts Entire Jet Fuel Market," *CNBC*, November 19, 2014, https://www.cnbc.com/2014/11/19/us-air-force-completes-jet-fuel-conversion-impacts-entire-jet-fuel-market.html.

[44] Brian Dodson, "Most Powerful Military Explosive Tamed for Use," *New Atlas*, September 10, 2012, https://newatlas.com/cl-20-high-power-military-explosive/24059; and Jacqueline Akhavan, "Explosive Power and Power Index," *IEEE Globalspec Engineering* 360, 2017, http://www.globalspec.com/reference/55654/203279/explosive-power-and-power-index.

[45] Chun Hong Kelvin Yap, "The Impact of Armor on the Design, Utilization and Survivability of Ground Vehicles: The History of Armor Development and Use," (Monterey, CA: Naval Postgraduate School, 2012), http://dtic.mil/dtic/tr/fulltext/u2/a567418.pdf; and Sydney J. Freedberg, Jr., "Milley's Future Tank: Railguns, Robotics, and Ultra-Light Armor," *Breaking Defense*, July 27, 2017, available at https://breakingdefense.com/2017/07/railguns-robotics-ultra-light-armor-general-milleys-future-tank.

[46] Paul B. Rehmus, "Alternatives for Future U.S. Space-Launch Capabilities," (Washington, DC: Congressional Budget Office, 2006), 11, 19, https://www.cbo.gov/sites/default/files/109th-congress-2005-2006/reports/10-09-spacelaunch.pdf; Peter B. de Selding, "SpaceX's New Price Chart Illustrates Performance Cost of Reusability," *Space News*, May 2, 2016, http://spacenews.com/spacexs-new-price-chart-illustrates-performance-cost-of-reusability.

[47] Michael E. O'Hanlon, "Forecasting Change in Military Technology, 2020-2040."

recent years, this trend has been particularly significant in commercial and civilian markets in areas such as remote communications, low-resolution Earth observation, and weather forecasting.[48] As discussed in my forthcoming book, *The Senkaku Paradox: Risking Great Power War Over Small Stakes*, militaries may greatly benefit as well, for example in creating more resilient communications networks less vulnerable to a small number of anti-satellite weapon attacks against large individual platforms.[49]

The basic means of getting to orbit have changed much less. Indeed, many of the systems still in operation—Atlas, Delta IV, Athena, Minotaur, Pegasus, and Taurus—were already in use in the 1990s. Some even employ Minuteman or "Peacekeeper"/MX surplus missiles as boosters, underscoring the point about how little has changed over the past generation.[50] Again, much greater progress could well loom, as reusable rockets show promise through the efforts of firms like SpaceX and Blue Sky. But to date, there has been no rocket revolution in modern times.

Progress in missiles has been more significant. Take for example air-to-air missiles. They can now range 200 miles and reach speeds of Mach 6, in some cases.[51] These are impressive characteristics. That said, the improvement of engines and aerodynamic features is probably again best viewed as evolutionary, not revolutionary. After all, the Phoenix air-to-air missile carried by the F-14 Tomcat starting in the 1970s had a range of more than 100 miles and a top speed of Mach 5. Much of the innovation in radar-guided and infrared-guided air-to-air missiles in recent decades has been in the realms of sensor and countermeasure technology. The competition between missiles and aircraft has arguably had less to do with kinematics and movement, and more to do with measures and countermeasures.[52]

Two more categories in this wide-ranging grab bag of platform-related technology are ships and stealth, the latter relating primarily to aircraft. In ship technology, my interest here is in the basic hydrodynamics of propulsion and of movement (sensor systems, missile defenses, engines, and other specific systems being covered separately in other technology categories). Here, progress has been modest. Some specific types of smaller ships do remarkable things. Some travel just above the water's surface, as with one variant of the Littoral Combat Ship, based partly on innovations associated with the 1991 Fincantieri Destrier vessel, or they employ triple hulls, as with the trimaran variant of the Littoral Combat Ship. Others capture their own wakes, as with the so-called Stiletto. Otherwise, however, basic physics continues to limit the performance of major vessels.[53] Notably, for example, the Gerald Ford class of aircraft carriers reportedly

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[48] Lucien Rapp, Victor Dos Santos Paulino, and Adriana Martin, "Satellite Miniaturization," (Toulouse, France: University of Toulouse, 2015), http://chaire-sirius.eu/wp-content/uploads/2015/07/Note-SIRIUS-Satellite-Miniaturization.pdf.

[49] Michael E. O'Hanlon, *The Senkaku Paradox: Risking Great Power War Over Small Stakes*.

[50] Nathan Daniels, "Current Space Launch Vehicles Used by the United States," (Washington, DC: American Security Project, April 2014), https://www.americansecurityproject.org/wp-content/uploads/2014/05/218841132-Current-Space-Launch-Vehicles-Used-by-the-United-States.pdf.

[51] Jeffrey Lin and P.W. Singer, "China Is Testing a New Long-Range, Air-to-Air Missile that Could Thwart U.S. Plans for Air Warfare," *Popular Science*, November 22, 2016, https://www.popsci.com/china-new-long-range-air-to-air-missile.

[52] On this set of issues, see for example, John Keller, "Can U.S. Air-to-Air Missiles Hit Their Targets Through Today's Enemy Electronic Warfare (EW)?" *Military and Aerospace Electronics*, April 12, 2016, http://www.militaryaerospace.com/articles/2016/04/ew-missiles-challenge.html; and Kyle Mizokami, "The Pentagon Is Working on a New Air-to-Air Missile," *Popular Mechanics*, November 2, 2017, http://www.popularmechanics.com/military/weapons/news/a28883/new-air-to-air-missile-amraam.

[53] See "M80 Stiletto," *Naval Technology*, 2017, http://www.naval-technology.com/projects/m80-stiletto; "Littoral Combat Ship," *Naval Technology*, 2017, http://www.naval-technology.com/projects/littoral; and Milan Vego, "No Need for High Speed," *Proceedings*, (September 2009): 46-50, https://www.usni.org/magazines/proceedings/2009-09/no-

moves at roughly the same speed as its predecessors, for example—something more than 30 knots (though it does have important new capabilities in terms of its various sub-systems, such as its electromagnetic launch system).[54] Other major ships such as Arleigh Burke-Class destroyers remain similar to previous generations, and also tend to operate in the 30-knot range—essentially the speed of warships of a century ago.[55]

A brief word on submarine quieting. This trend continues through the classic methods of isolating machinery within a submarine, using anechoic materials on its surface, and of course further extending "snorkeling time" through air-independent propulsion and related methods. However, all of these efforts were underway in the late 20th century and they do not seem to be accelerating so much as proliferating to more countries.[56] The Seawolf attack submarine, designed by the United States in the latter Cold War period, reportedly did have huge new advantages in quietness (up to a factor of 10 by some reports), and an ability to dive much deeper than other submarines. But apparently these benefits were not seen as being worth the cost once the Cold War ended, and the program was severely curtailed.[57]

Regarding aircraft stealth, progress continues. Materials that are less inclined to degradation or to heating (which produces potentially detectable infrared signatures for an aircraft that may be stealthy against radar but not in other ways), and easier to maintain are continually being pursued and in some cases deployed.[58] However, big breakthroughs in stealth may have slowed relative to the late 20th century. Indeed, the F-35 aircraft is estimated to be less stealthy than the F-22 or B-2—not because technology reverted back to an earlier state, of course, but because economies were accepted in its design in order to make the aircraft more affordable. Still, the progress underlying stealth technology has apparently not been so fast as to make a $100 million per copy fighter as stealthy as its predecessor. That is notable.[59]

Other weapons

Finally, there is a category of technologies that might be grouped under the pedestrian phrase "other weapons." They range from nonlethal devices of various kinds, to biological weapons and other weapons of mass destruction, to lasers and particle beams, to rail guns and long-range kinetic strike systems. Here the broadest useful single-sentence summary that might be offered of these technologies is that research continues in some very interesting directions, potentially setting up important milestones over the next 20 years—but there have not been many dramatic developments in the last 20.

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need-high-speed.

[54] Kyle Mizokami, "First of Its Class, America's Newest Aircraft Carrier Is Underway at Sea," *Popular Mechanics*, April 10, 2017, http://www.popularmechanics.com/military/navy-ships/news/a26014/gerald-ford-carrier-is-underway-at-sea; and Akanksha Gupta, "The 10 Biggest Aircraft Carriers," *Naval Technology*, July 5, 2017, http://www.naval-technology.com/features/feature-the-10-biggest-aircraft-carriers_4067861-4067861.

[55] Michael O'Hanlon, *Technological Change and the Future of Warfare*, 80; and "Destroyers DDG," U.S. Navy, 2017, http://www.navy.mil/navydata/fact_display.asp?cid=4200&tid=900&ct=4.

[56] "The Stirling Engine: An Engine for the Future," Saab, 2017, http://saab.com/naval/Submarines-and-Warships/technologies/The-Stirling-Engine; and Kyle Mizokami, "The Kilo-Class Submarine: Why Russia's Enemies Fear 'The Black Hole,'" *The National Interest*, October 23, 2016, http://nationalinterest.org/blog/the-kilo-class-submarine-why-russias-enemies-fear-the-black-18140.

[57] Kyle Mizokami, "Why Russia and China Fear America's Seawolf-Class Submarines," *The National Interest*, October 22, 2016, http://nationalinterest.org/blog/why-russia-china-fear-americas-seawolf-class-submarines-18138.

[58] Kris Osborn, "The U.S. Air Force Is Doing All It Can to Keep the B-2 Bomber Stealth," *The National Interest*, June 6, 2017, http://nationalinterest.org/blog/the-buzz/the-us-air-force-doing-all-it-can-keep-the-b-2-bomber-21020.

[59] John Pike, "Radar Cross Section," *Globalsecurity.org*, November 7, 2011, https://www.globalsecurity.org/military/world/stealth-aircraft-rcs.htm.

Start with nonlethal weapons, including radio-frequency and microwave weapons. Ideally, these would allow ways to incapacitate individuals or vehicles or otherwise prevent deadly uses of force especially in places where using lethal force could hurt innocent people. Urban settings and counterinsurgency environments are among the most relevant places where nonlethal weapons could be of considerable utility. Thus, Iraq and Afghanistan and such places come to mind. Unfortunately, as the wars of the 21st century have demonstrated to date, lethal ordnance remains the coin of the realm for almost all tactical settings.[60] Whether it is stopping a suspicious truck that might be a bomb, or freezing a shooter immersed within a civilian crowd, or creating a perimeter around a protected asset into which potential threats cannot be allowed access, lethal weaponry is still the default mechanism by which American forces and their allies and friends protect themselves.

Recent DoD documents on nonlethal weapons emphasize research programs, demonstration projects, and online classes where volunteers can learn more about the technologies—less so empirical analyses of actual uses of nonlethal weapons in tactically significant ways.[61] Devices like high-powered microwave weapons to stop engines with advanced electronics, or sonic weapons that reliably push away threats while safely protecting innocents, or tranquilizer weapons that provide dependable ways to stop an enemy combatant without necessarily killing him or her do exist. Similar progress is reported abroad, in countries such as Russia.[62] But their tactical utility tends to be modest, to date.[63] This general proposition is seen not only on foreign battlefields but in the inner cities of the United States, where police fight crime as well; apart from the time-tested tear gas and the occasional use of a taser, firearms still dominate the tactical setting when force is required.[64]

Rail guns are not unlike microwave weapons in having experienced considerable progress in the research and development realms in recent decades. They are closer to being part of a major military breakthrough or "revolution" than before. However, it seems likely that even at the conclusion of the 2000-2020 time period, they will still be best viewed as emerging technologies rather than deployed systems.[65]

Consider next weapons of mass destruction. At the risk of some oversimplification, it seems reasonable to assert that chemical and nuclear weapons technologies are fairly mature, evolving only modestly if at all. The Chemical Weapons Convention has constrained research and production of chemical agents. The Russians appear to have violated this treaty recently with the nerve agent Novichok, used in the 2018 attack on the former Soviet spy Sergei Skripal and his daughter in Britain. But even that agent was

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[60] Dan Lamothe, "The U.S. Military Has Pain Rays and Stun Guns. So Why Aren't They Being Used?" *The Week*, August 7, 2014, http://theweek.com/articles/445332/military-pain-rays-stun-guns-why-arent-being-used.

[61] A notable case in point is "DoD Nonlethal Capabilities: Enhancing Readiness for Crisis Response," (Washington, DC: Department of Defense, 2015), http://jnlwp.defense.gov/Portals/50/Documents/Press_Room/Annual_Reviews_Reports/2015/FINAL_DoD_%20ANNUAL_%20REVIEW_PRINTER2_PDF_WEBSITE%20_Small_2Oct2015.pdf.

[62] Michael Peck, "Russia's Next Military Game Changer: Microwave Weapons?" *The National Interest*, July 12, 2016, http://nationalinterest.org/feature/russias-next-military-game-changer-microwave-weapons-16946.

[63] Kevin Robinson-Avila, "The Army Is Testing a Microwave Weapon System in the Mountains of New Mexico," *Task and Purpose*, May 21, 2017, http://taskandpurpose.com/army-microwave-weapon.

[64] For a good summary of the recent state of play in research, see Katie Drummond, "Exposed: The Military's Freakiest 'Non-Lethal' Weapon Ideas," *Wired*, January 3, 2012, https://www.wired.com/2012/01/non-lethal-weapons; and "Current Non-Lethal Weapons," Department of Defense, 2017, http://jnlwp.defense.gov/Current-Non-Lethal-Weapons.

[65] Andrea Shalal, "U.S. Military Sees More Use of Laser, Microwave Weapons," *Reuters*, July 28, 2015, https://www.reuters.com/article/us-usa-military-arms/u-s-military-sees-more-use-of-laser-microwave-weapons-idUSKCN0Q22HH20150728.

developed by the early 1990s.[66] There does not appear to have been much advancement in relevant technologies since.

The Nuclear Test Ban Treaty, though never ratified, has been respected by the major nuclear powers since the 1990s and impeded fundamental new work on nuclear explosives. Much nuclear research in the United States since then has gone into stewardship of the existing arsenal.[67] Much academic and scholarly writing about the bomb has emphasized nonproliferation, arms control, and disarmament rather than technical advancement.[68] Recent reports by the U.S. intelligence community focus their arms control sections on the use of sarin by the Syrian government, on violations of the Intermediate-Range Nuclear Forces Treaty by Russia, and on modernization of Chinese ballistic missiles and submarines. Underlying chemical and nuclear technologies are not generally the major subjects of concern or attention.[69]

Where some progress has continued is in the biological realm. But even here, what has changed has much more to do with basic biology—understanding the human genome, splicing genes, and so forth. Diseases themselves as such, and attacks with biological weapons, have not progressed, nor has the imminent danger of any such attacks in the future, as best as can be discerned from available evidence. There was a flurry of interest in biological weapons after the 2001 anthrax attacks in the United States. But since then, it seems reasonable to conclude that public policy has focused more on naturally occurring biological pathogens, most notably Ebola, rather than on the development of biological warfare or preparations for the latter (offensive or defensive).[70] The world may be poised for much more radical changes, and graver dangers, in future biological weaponry. But it seems fair to conclude that the first two decades of this century have been a relatively quiet period for the advancement of this kind of technology of warfare as well.

As noted above, particle beams remain of very specific utility for certain purposes only, given their expense and size and basic physics. Lasers are starting to come of age as weapons, though the more important milestones seem likely to occur in the next 20 years than in the 2000-2020 time block. Although the 2000-2020 time period saw the cancellation of the Airborne Laser Program as a priority means of missile defense, it did witness the deployment of smaller lasers on ground vehicles and the beginning of a serious effort to weaponize a laser self-defense system for fighter aircraft. The latter, known as the Self-protect High Energy Laser Demonstrator, or SHiELD, is to be prototyped by 2021 according to current plans.[71]

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[66] See for example, Will Englund, "What a Brave Russian Scientist Told Me about Novichok, the Nerve Agent Identified in the Spy Attack," *The Washington Post*, March 12, 2018, https://www.washingtonpost.com/news/worldviews/wp/2018/03/12/what-is-novichok-the-russian-nerve-agent-and-the-scientist-who-revealed-it/?utm_term=.f7a478ed98b7.

[67] Stephen M. Younger, *The Bomb: A New History* (New York: Harper-Collins Publishers, 2009); and James E. Doyle, *Renewing America's Nuclear Arsenal: Options for the 21st Century* (London: International Institute for Strategic Studies, 2017), 24-28, 82-83.

[68] Richard L. Garwin and Georges Charpak, *Megawatts and Megatons: A Turning Point in the Nuclear Age?* (New York: Alfred A. Knopf, 2001); Harold A. Feiveson et al., *Unmaking the Bomb: A Fissile Material Approach to Nuclear Disarmament and Nonproliferation* (Cambridge, MA: MIT Press, 2014); and Arnie Heller, "Stockpile Stewardship at 20 Years," (Livermore, CA: Lawrence Livermore National Laboratory, 2015), https://str.llnl.gov/july-2015/verdon.

[69] Daniel R. Coats, "Worldwide Threat Assessment of the U.S. Intelligence Community," (testimony, Senate Select Committee on Intelligence, Washington, DC May 11, 2017), https://www.dni.gov/files/documents/Newsroom/Testimonies/SSCI%20Unclassified%20SFR%20-%20Final.pdf.

[70] It is striking how many of the review articles on biological weapons and warfare turned up by standard searches were written in the last years of the 20th century or 2001 and 2002. There has generally been much less literature since, it would appear. See for example, "Overview of Potential Agents of Biological Terrorism," Southern Illinois University, 2017, https://www.siumed.edu/im/overview-potential-agents-biological-terrorism.html.

[71] Valerie Insinna, "Coming in 2021: A Laser Weapon for Fighter Jets," *Defense News*, November 7, 2017, https://www.defensenews.com/air/2017/11/07/coming-in-2021-a-laser-weapon-for-fighter-jets.

Finally, consider long-range strike systems, and specifically the idea of a Conventional Prompt Global Strike capability. These could be based on hypersonic cruise missile concepts or could employ ballistic missiles armed with conventional warheads rather than nuclear weapons. Although they have been an object of interest in recent years, the high costs associated with most concepts, combined with the potential risks to strategic stability, have prevented formation of any consensus on how to proceed to a deployed system. More exotic ideas like long-range, intercontinental rail guns have also not progressed. As such, this remains a set of technologies with potential but without any notable influence on fielded military forces, as the first 20 years of the 21st century gradually come to a close.[72]

SYNOPSIS

There were relatively few major surprises in the evolution of military technology in the first two decades of the 21st century. As such, if I were to grade my own homework, or compare my prognostications from 2000 with what appears to be the reality of deployed weaponry and achievable operational concepts as we near 2020, I would, at the risk of provoking hecklers, suggest a grade of A-minus. Progress was modest in most sensor technologies. It was also modest in most major weapons platforms—that is, the vehicles, aircraft, ships, propulsion systems, fuels, and related foundational machinery of a deployable military. Technologies such as stealth aircraft and diesel-electric submarines with air-independent propulsion proliferated and improved, but the basic breakthroughs had already occurred (and been deployed) already in the 20th century.

Computers advanced very fast. This was a general conclusion applicable across hardware and software, and in civilian technologies as well as military ones. Indeed, advances in the former were so consequential as to have many implications for military domains. This dynamic has produced, for example, encrypted technologies for communications now available to terrorists, social media methods of recruiting and organizing extremists through virtual networks, and accurate navigational aids available to insurgents on the modern battlefield that can help them improvise precision-strike capabilities.

Other types of weapons such as microwave weapons and high-power lasers made good progress in the laboratories but remained of very limited capability in the field; wide-scale deployment remains a future prospect. Biological weapons, nonlethal weapons, and biological and chemical sensors probably progressed slower than I had foreseen.

As a result, trends in warfare that I foresaw back in 2000 were indeed largely the reality of the battlefields of the 2000s and 2010s, even if I hardly succeeded in predicting which wars would be fought or where they would be contested. High-end precision-strike warfare remained a strength of the United States, and gradually became a greater strength of other countries with the resources and strong military institutions to pursue it, like China and Russia. Infantry and counterinsurgency and counterterrorism operations remained very difficult, however, even for the world's best militaries. This was a function largely of the unavailability of sensors that could reliably find enemy infantry fighters at distance, as well as the continued unavailability of technologies that could stymie the effectiveness of simple weapons like AK-47s and improvised explosive devices available to even the most rudimentary of militias or terrorist forces.

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[72] See James M. Acton, *Silver Bullet?: Asking the Right Questions About Conventional Prompt Global Strike* (Washington, DC: Carnegie, 2013); and Amy F. Woolf, "Conventional Prompt Global Strike and Long-Range Ballistic Missiles: Background and Issues," (Washington, DC: Congressional Research Service, April 6, 2018, https://fas.org/sgp/crs/nuke/R41464.pdf.

To the extent I was largely vindicated by technical developments and events, that is no indication of particular clairvoyance or brilliance on my part. Rather, a systematic examination of trends in major areas of defense technology creates an analytical process that tends to point in a relatively clear direction, at least when one is looking out no more than roughly 20 years or so. Indeed, since many major weapons programs require 20 years to acquire, one can often "see the future" two decades in advance simply by looking at what weapons laboratories and military services are researching today. This method is not foolproof but works more often than not.

Yet, as noted before, there is also a major caveat that emerges from this discussion. In areas where I was insufficiently appreciative of the likely change that could result in military-related technologies, lessons emerge about how to improve the approach going forward.

Looking over the 2000-2020 period, just as impressive as the continued relevance of "Moore's Law" in predicting improved computing speed and capacity is the growth of cyber vulnerability concerns across virtually all domains of military systems. Indeed, the concern extends to civilian systems that support military operations, such as transportation networks and electricity grids. Computer systems have been introduced somewhat carelessly into virtually all domains of military equipment and operations, with little regard for years about how an enemy might exploit the resulting opportunities for hacking. Back in the 1990s, computers were known to be vulnerable. But the greatest worries were often seen as growing pains for a new technology, such as concern over what would happen in 2000 due to the "Y2K" phenomenon (the possibility that civilian as well as military systems that had not been programmed to keep operating past the year 2000 would systemically fail when that year arrived). Today, by contrast, cyber vulnerability of major weapons platforms, many still using well-known civilian software that contain vulnerabilities hackers can use to enter, hack, or spoof remote systems including those used by militaries, is rampant and largely unmitigated.

More positive, perhaps, from a U.S. standpoint, has been the remarkable chain of improvements in robotics technologies such as drones, and in other types of miniaturized systems such as satellites. This progress was probably greater than I had projected back in 2000—perhaps because the synergies created by greater computing power and miniaturization, tested and refined on the real battlefields of the Middle East, created innovative dynamics that were difficult to anticipate by looking at individual areas of technology.

The central lesson here would appear to be that even if one can forecast progress in specific technologies, one cannot as easily foresee how military organizations will combine them and integrate them into new concepts of operations. Multi-step innovations that involve several areas of military technology as well as the performance of complex human organizations are much harder to anticipate. In a way, this is stating the obvious. More complex systems are harder to understand, and therefore harder to predict. But a review of these areas of military technology provides a more granular and tangible feel for why this is so, and helps caution us about where we are most able to prognosticate with some degree of accuracy in the future.

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