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ARTICLE

Looking back to look forward: Autonomous systems, military revolutions, and the importance of cost

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ABSTRACT
Autonomous systems are often lauded as revolutionary. However, what makes them revolutionary is still up for debate. We identify assumptions about the revolutionary effect of autonomy and draw on historical work to examine how these characteristics have affected past conflicts. Our look at the past suggests where these systems may be most revolutionary is in cost mitigation—both political and economic. Mitigating economic cost helps create mass, firepower, and resiliency while mitigating political cost allows states to control force with escalation risks and domestic support. This balance is key for states that rely on autonomous systems to win competition strategies.

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Autonomous and unmanned[1] systems – from satellites to long range strategic reconnaissance aircraft, swarms of intelligent sensors, and increasingly smart missiles – are now a major component of modern military arsenals. The U.S. Department of Defense (DoD) has made these technologies a key investment priority, investing billions of dollars in unmanned systems.[2] Former Deputy Secretary of Defense Bob Work went so far as to declare that the rise of autonomous and unmanned technologies would not only 'change the way that war is waged, but

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[1]We use the term unmanned because it is the most common way to describe systems without a human physically in the platform. However, uninhabited may also be an appropriate way to think about many of these systems. On how gender informs these technologies, see: Mary Maniikan, 'Becoming Unmanned: The Gendering of Lethal Autonomous Warfare Technology', *International Feminist Journal of Politics*, 16/1 (2014), 48–65.

[2]Department of Defense, *Summary of the National Defense Strategy of the United States of America*, 2018. https://dod.defense.gov/Portals/1/Documents/pubs/2018-National-Defense-Strategy-Summary.pdf; 116th Congress, *National Defense Authorization Act for Fiscal Year* 2020. https://www.congress.gov/bill/116th-congress/senate-bill/1790.

that I am starting to believe very, very deeply that is also going to change the *nature* of war'.[3]

Despite the strong belief that unmanned and autonomous systems will create revolutionary effects on the battlefield, what exactly makes these systems more or less revolutionary is still largely unresolved.[4] For some, autonomy creates speed, precision, range, or decision advantage, creating decisive tactical and operational advantages for states that adopt autonomy appropriately.[5] However, for others, autonomy is a technological substitute for missions that are 'dull, dirty, or dangerous'.[6] Too often these narratives elide and autonomous systems become all things, an expensive acquisition hedging strategy in which the US Department of Defense and its armed services invest across a wide array of mission sets and capabilities in the hope that one of these investments will provide some sort of decisive advantage. But this exploratory investment strategy is both expensive and potentially distracts resources and time away from more fruitful uses of unmanned technologies.

So, what is the competitive edge provided by unmanned technology? While many previous explorations of autonomy and military effectiveness looked to the future to divine the impact of these technologies on conflict, in this paper we instead look back historically and examine how technology created revolutions in military power in past eras. In doing so, we lean on the work of Williamson Murray, who opined, 'no revolution has ever involved a leap into the future without a lifeline to past military concepts and capabilities'.[7] In examining the historical context of technologies and revolutions, we argue that

[3]Sydney Freedberg, 'War Without Fear: DepSecDef Work on How AI Changes Conflict', *Breaking Defense*, May 31, 2017. https://breakingdefense.com/2017/05/killer-robots-arent-the-problem-its-unpredictable-ai/.

[4]Antonio Calcara, Andrea Gilli, Mauro Gilli, Raffaele Marchetti, and Ivan Zaccagnini. 'Why Drones Have Not Revolutionized War: The Enduring Hider-Finder Competition in Air Warfare', *International Security* 46/4 (2022), 130–171.

[5]Christian Brose, 'The New Revolution in Military Affairs: War's Sci-Fi Future', *Foreign Affairs*. 98 (2019), 122; Ulrike Esther Franke, 'The Unmanned Revolution: How Drones are Revolutionising Warfare', PhD diss., Oxford Univ., 2018; Tamir Libel and Emily Boulter, 'Unmanned Aerial Vehicles in the Israel Defense Forces: A Precursor to a Military Robotic Revolution?', *The RUSI Journal* 160/2 (2015), 68–75; Maxim Worcester, 'Autonomous Warfare: A Revolution in Military Affairs', *ISPSW Strategy Series: Focus on Defence and International Security* 340 (2015); Daniel Sukman, 'Lethal Autonomous Systems and the Future of Warfare', *Canadian Military Journal* 16/1 (2015): 44–53; Kai-Fu Lee, 'The Third Revolution in Warfare', *The Atlantic*, September 11, 2021; Peter Warren Singer, *Wired for War: The Robotics Revolution and Conflict in the 21st Century*, New York: Penguin, 2009.

[6]Peter Singer, 'A Revolution Once More: Unmanned Systems and the Middle East', *Brookings Institute*, October 29, 2009. https://www.brookings.edu/articles/a-revolution-once-more-unmanned-systems-and-the-middle-east/; Richard Schwing, *Unmanned Aerial Vehicles-Revolutionary Tools in War and Peace*, (Carlisle Barracks: Army War College), 2007; Adam Stulberg, 'Managing the Unmanned Revolution in the US Air Force' *Orbis* 51/2 (2007), 251–265; Michael Spigelmire and Timothy Baxter, *Unmanned Aircraft Systems And the Next War*. (Redstone Arsenal: Office of the Project Manager Unmanned Aircraft Systems 2013).

[7]Williamson Murray, *Thinking About Revolutions in Military Affairs* (Washington, DC: Assistant Secretary of Defense Public Affairs 1997), 8.

technological characteristics – lethality, range, maneuver, precision – rarely create long term advantages for states. Instead, our analysis shows that for technology to have truly revolutionary effects on the outcomes of war, it has to change the economic and political cost of warfare. Mitigating economic and political cost allows states to sustain conflict for long-term strategic success – both in terms of economic support and domestic political support. We then apply these theories of cost and military revolutions to a range of autonomous systems – including sensors, munitions, and platforms – to finally recommend a new investment strategy for autonomous systems within modern militaries.

Below, we detail the historical narrative of military revolutions and trace the role of technology in creating revolutionary military advances. We then apply these historical lessons to arguments about unmanned effectiveness and examine what these historical revolutions suggest about the most impactful use of unmanned systems today. Finally, we conclude with implications for the U.S. as it thinks about how to best use unmanned systems for great power competition.

Military revolutions and revolutions in military affairs

Current unmanned technology discussions lean heavily on perceptions of warfare and history[8] that emerged at the end of the Cold War,[9] and

[8]Clifford Rogers, (ed.), *The Military Revolution Debate: Readings on the Military Transformation of Early Modern Europe (*New York: Westview Press 1995); Steven Metz, *Strategy and the Revolution in Military Affairs: From Theory to Policy* (New York: DIANE Publishing 1995); Geoffrey Parker, *The Military Revolution: Military Innovation and the Rise of the West, 1500–1800* (Cambridge: Cambridge University Press 1996); David Parrott, *The Business of War: Military Enterprise and Military Revolution in Early Modern Europe* (Cambridge: Cambridge University Press 2012); Colin S. Gray, *Strategy for Chaos: Revolutions in Military Affairs and the Evidence of History* (London: Frank Cass 2002); Steven Metz and James Kievit, *Strategy and the Revolution in Military Affairs: From Theory to Policy* (Carlisle: Strategic Studies Institute 1995); Wim Smit and John Grin, *Military Technological Innovation and Stability in a Changing World: Politically Assessing and Influencing Weapon Innovation and Military Research and Development*, Charlotte: Virginia University Press, 1992; Max Boot. *War Made New: Technology, Warfare, and the Course of History, 1500 to Today*, (New York: Penguin 2006); Allan R. Millett and Williamson Murray, (eds.), *Military Effectiveness: Volume 2, The Interwar Period* (Cambridge: Cambridge University Press 2010); Michael O'Hanlon, *Technological Change and the Future of Warfare* (Washington D.C.: Brookings 2000); Alvin Toffler and Heidi Toffler, *War and Anti-War: Survival at the Dawn of the 21st Century (*Boston: Little, Brown, 1993); Michael Roberts, *The Military Revolution, 1560–1660* (New York: Routledge 2018); Keith Shimko, *The Iraq Wars and America's Military Revolution*, Cambridge: Cambridge University Press, 2010; Mahinder Kingra,'The Trace Italienne and the Military Revolution During the Eighty Years War, 1567–1648', *The Journal of Military History* 57/3 (1993), 431.

[9]For a comparative analysis of the rise of the U.S. revolution in military affairs literature and similar waves in Soviet and Israeli defense circles see Dima Adamsky, *The Culture of Military Innovation: The Impact of Cultural Factors on the Revolution in Military Affairs in Russia, the US, and Israel* (Stanford: Stanford University Press 2010).

that reached their apex in the early 2000s as the Revolution in Military Affairs.[10] According to this understanding,

> military revolutions recast society and the state as well as military organizations. They alter the capacity of states to create and project military power. And their effects are additive. States that have missed the early military revolutions cannot easily leap-frog to success in war by adopting the trappings of military technology.[11]

According to this theory, history is a progression of military revolutions in which technologies in conjunction with societal, doctrinal, and tactical adaptations, make states qualitatively (and exponentially) better at warfare than their adversaries. Much like Darwin's evolutionary theory, the states that adapt best to these revolutions survive while those that fail to adapt become either obsolete or irrelevant to international politics.

Technology plays a pivotal role in many of these revolutions, often by providing an impetus for a punctuated equilibrium in which first mover states disrupt status quo capabilities and surpass adversaries.[12] States able to harness revolutionary technologies – for example, the longbow, gunpowder, steam, telegraph, railroad, or mechanization – subsequently vault to the top of the international system. As Max Boot argues, 'technology sets the parameters for the possible, it creates the potential for a military revolution'.[13]

Those that fail to adapt quickly enough decrease in power and anecdotes within this literature often highlight these revolutionary missteps. As Boot asserts, 'the Mongols missed the Gunpowder Revolution; the Chinese, Turks, and Indians missed the Industrial Revolution; the French and British missed

[10]Highlights from this very rich discussion about the revolution in military affairs and defense technology include: Eliot Cohen, 'A Revolution in Warfare', *Foreign Affairs* 75/2 (1996), 37–54; Andrew F. Krepinevich, *The Military-Technical Revolution: A Preliminary Assessment* (Washington D.C.: Center for Strategic and Budgetary Assessments 1992); Frank Kendall, 'Exploiting the Military Technical Revolution: A Concept for Joint Warfare', *Strategic Review* (Spring 1992), 25; Thomas G. Mahnken and James R. Fitzsimonds, *The Limits of Transformation: Officer Attitudes Toward the Revolution in Military Affairs* (Newport, RI: Naval War College Press 2003); Elinor Sloan, *Revolution in Military Affairs* (McGill: McGill-Queen's Press 2002); William Owens, *The American Revolution in Military Affairs* (Washington: Joint Chiefs of Staff 1996); David Jablonsky, 'US Military Doctrine and the Revolution in Military Affairs', *Parameters* 24/3 (1994), 18; Stephen Peter Rosen, 'The Impact of the Office of Net Assessment on the American Military in the Matter of the Revolution in Military Affairs', *The Journal of Strategic Studies* 33/4 (2010), 469–482; Emily Goldman and Thomas Mahnken, (eds.), *The Information Revolution in Military Affairs in Asia* (New York: Springer 2004).

[11]Macgregor Knox and Williamson Murray, (eds.), *The Dynamics of Military Revolution,1300–2050* (Cambridge: Cambridge University Press 2001), 7.

[12]On the assumptions about technology and its role in RMA, see (for both critique and support): David Burbach and Brendan Rittenhouse Green, 'The technology of the revolution in military affairs', in *US Military Innovation since the Cold War* (New York, NY: Routledge 2009), 30–58; Peter J. Dunn, 'Time x technology x tactics= RMA: Why we Need a Revolution in Military Affairs and How to Begin It!' *Australian Defence Force Journal* 116 (1996), 11–18; Earl H. Tilford Jr., *The Revolution in Military Affairs: Prospects and Cautions* (Carlisle Barracks: Army War College Strategic Studies Institute 1995); James R. Fitzsimonds and Jan M. Van Tol. *Revolutions in Military Affairs* (Washington: Office of the Secretary of Defense 1994).

[13]Boot, *War made New: Technology, Warfare, and the Course of History, 1500 to Today*, 10.

major parts of the Second Industrial Revolution; the Soviets missed the Information Revolution'.[14] Indeed, the idea of the bumbling officer unable to see the impact of new technology on warfare is a constant theme – none more so than the poor Field Marshal Haig, quoted in a series of military revolutions analyses for a 1925 unfortunate assessment: 'you find just as much use for the horse – the well-bred horse – as you have ever done in the past'.[15]

Looking back to look forward: How technology creates revolutions

This predominantly US strategist approach to revolutions in military affairs focuses heavily on how technological characteristics that increase speed, range, precision, or lethality can produce revolutionary changes in power. However, others were less convinced that technology alone could create revolutionary changes in military power.[16] For these scholars, there was an important difference between what Williamson Murray defined as military revolutions – a series of events that 'recast the nature of society and the state as well as of military organizations'[17] and much smaller revolutions in military affairs – more akin to aftershocks within and around a military revolution. RMAs drove short-term tactical or operational asymmetries while, in contrast, military revolutions 'altered the capacity of states to project military power and allowed the military to kill people and break things ever more effectively'.[18]

Whereas RMAs produce advantages in operational characteristics of warfare: for example, mass, firepower, range, maneuver, precision – revolutions create strategic advantages in the economic and political cost of war – they change the ability to sustain war over time. In order to sustain war to victory,

[14] Ibid, 455.

[15] Andrew Bacevich, 'Preserving the Well-Bred Horse', *The National Interest* 37 (1994), 43–49. This, as many have pointed out, is perhaps an unfair historical legacy attributed to Haig who spearheaded a series of technological innovations within the British army. See Andrew Wiest, *Haig: The Evolution of a Commander* (New York: Potomac Books, Inc. 2005).

[16] This distinction between military revolutions and revolutions in military affairs helps explain why there is a significant difference in the cases that historians and strategists classify as revolutionary. Knox and Murray, for instance, identify four periods of time as military revolutions, beginning with the 17th century, the French and industrial revolutions, and moving into the first world war and 20th century missiles. Similarly, Max Boot identifies 4 military revolution time periods that roughly correlate with Knox and Murray but differentiates the mechanisms which define the age as revolutionary. Neither of these categorizations include the period before gunpowder – to include the invention of the longbow or the rise of the trace italienne – which many military historians identify as part of early Western state military innovations. These cases are included in Krepinevich's accounting which, in contrast to these broad categorizations of periods of military revolutions, details ten revolutions in military affairs, which focus more closely on specific technological or political innovations, moving from the 15th century to the information age today.

[17] Murray, *Thinking About Revolutions in Military Affairs*, 3.

[18] Ibid, 3.

a regime must have both the economic power to fund conflicts and the political control to raise funds and mobilize their citizenry. Economic costs of warfare create political costs when, in order to maintain conflict, the regime levies taxes, material depravation, or universal conscription.[19] Military revolutions, therefore, occur when a state is able to harness revolutionary changes in society or technology to mitigate the political and economic costs of conflict over time. As Williamson Murray and Macgregor Knox explain, 'military revolutions recast society and the state as well as military organizations. They alter the capacity of states to create and project military power'.[20] A brief look at military revolutions across time, and their relationship with revolutions in military affairs, helps illustrate why economic and military cost are so integral to how technologies (like our autonomy case) culminate to create true revolutions in military power.

The importance of economic and political cost to military revolutions can be traced back to RMAs of early Europe. The infantry revolution, a period of time from roughly the mid fourteenth century to the mid fifteenth century, featured weapons that shifted battle outcomes away from cavalry charges to infantry advances and raids.[21] These operational changes also altered the cost of war, ultimately changing which regimes were able to embark upon and win conflicts. Prior to the infantry revolution, cavalry and knights dominated war because they were faster, more maneuverable, and more heavily armoured than infantry. The advent of the longbow (in particular the sturdier and larger English longbow) as well as the spike negated the advantage of knights' maneuver in many terrains. The bow and the spike could make contact earlier than a sword, even if a horse was faster than a dismounted infantry-man, creating a first strike advantage for spikemen and archers. Also, because of the increased lethality of these systems (due to modifications in the fabrication of the English long bow in particular) armour was now vulnerable, negating knights' ability to withstand that first strike.[22] The

[19]On the relationship between economic cost of warfare and regimes, see Sarah Kreps, *Taxing Wars: The American Way of War Finance and the Decline of Democracy* (Oxford: Oxford University Press 2018); Charles Tilly, *Coercion, Capital, and European states, AD 990-1992* (New York, NY: Wiley-Blackwell 1992); Kenneth Schev and David Stasavage, 'The Conscription of Wealth: Mass Warfare and the Demand for Progressive Taxation', *International Organization* 64/4 (2010), 529–561; Rosella Cappella Zielinski, *How States Pay for Wars* (Cornell: Cornell University Press 2016).

[20]Williamson Murray and Macgregor Knox, 'Thinking about revolutions in warfare', *The Dynamics of Military Revolution: 1300–2050*, 7.

[21]Clifford J. Rogers, 'The Military Revolution in History and Historiography', in *The Military Revolution Debate: Readings on the Transformation of Early Modern Europe*; Christopher Allmand, '5. New Weapons, New Tactics', in (e,d.) Geoffrey Parker, *The Cambridge History of Warfare* (Cambridge: Cambridge University Press, 2020), 85–100; Clifford J. Rogers, '"As If a New Sun had Arisen": England's 14th Century RMA', in (eds.), Macgregor Knox and Williamson Murray, *The Dynamics of Military Revolution*, 15–34; Donald Featherstone, *Bowmen of England* (New York, NY: Grub Street Publishers 2011); M.J. Strickland and Robert Hardy, *The Great Warbow: From Hastings to the Mary Rose* (London: Sutton 2005); Gervase Phillips, 'Longbow and Hackbutt: Weapons Technology and Technology Transfer in Early modern England', *Technology and Culture* 40/3 (1999), 576–593.

[22]Rogers, *The Military Revolution Debate: Readings on the Military Transformation of Early Modern Europe*.

longbow and pike increased the distance between the human and the act of killing, allowed for more maneuverable raiding tactics,[23] and increased the lethality of existing weapons. However, none of these characteristics were enough for a complete theory of victory. Instead, their revolutionary effect was in how these weapons mitigated economic cost and therefore increased mass (or people) a leader could put on the battlefield for a comparable investment.

As Rogers recounts, 'the extremely high cost of this [a knight's] equipment, which in the mid-thirteenth century cost about £32 (over ten years' wages for a foot archer), strictly limited the number of knights and men-at-arms in medieval armies. By contrast, a well-equipped bowman of the early fifteenth century could buy all his arms and armor-a bow, sheaf of arrows, sword, bascinet, and brigantine – for £1 6s 8d. A crossbowman could potentially pay as little as 15s 4d for a crossbow, sword, bascinet, and jack-about one-fortieth the cost of the knight's equipment'.[24] Similarly, Allen and Leeson argue it was politically stable rulers' ability to equip mass swathes of the population with the cheaper longbow that gave England an innovation edge over the more tenuous regime in France.[25] By mitigating economic cost through state investments in both longbows and their archers, armies were able to equip more infantry-men, which then enabled the first-strike, more lethal, and more maneuverable tactics required for the infantry revolution.

In contrast to the infantry revolution which advantaged the offense and states able to leverage the cheaper technologies, the next two centuries were a battle of economic attrition between innovations in offense (high firepower artillery) and defense (fortifications and the trace italienne). The new cannons, which introduced dramatic improvements in firepower, were initially bulky, difficult to build, and required extensive logistical support.[26] This limited the extent of the early cannon's impact on campaigns. However, with developments in metallurgy, gunpowder, and wheeled trailers, cannons became cheaper to use and more versatile against inland targets.

States, in turn, had to adapt to artillery's firepower innovation with a new style of fortifications known as the *trace italienne*.[27] Made famous

[23]These raiding tactics also influenced the cost of war for the adversary. As Allmand details about the English raids on French territory, 'the principal aim was to weaken the enemy's morale and his ability to pay taxes'. Allmand, 'New Weapons, New Tactics', 89.
[24]Ibid.
[25]Douglas W. Allen and Peter T. Leeson, 'Institutionally Constrained Technology Adoption: Resolving the Longbow Puzzle', *The Journal of Law and Economics* 58/3 (2015), 683–715.
[26]Geoffrey Parker, 'The Gunpowder Revolution', in (ed.), Geoffrey Parker, *The Cambridge History of Warfare*, 101–116.
[27]Kingra, 'The Trace Italienne and the Military Revolution during the Eighty Years War, 1567–1648', 431; Christopher Duffy, *Siege Warfare: The Fortress in the Early Modern World 1494–1660* (New York, NY: Routledge 2013); Frank Tallet, *War and Society in Early Modern Europe: 1495–1715* (New York, NY: Routledge 2016); Charles Oman, *A History of the Art of War in the Sixteenth Century* (New York, NY: Routledge, 2018).

in Italy, the defense technologies created in response to the introduction of artillery included revolutions in masonry construction of angled bastions, moats, and ramparts. These fortification improvements created enormous cost for offensive states pursuing siege warfare (which became prolonged endeavours) and negated the firepower advantages of the artillery revolution. Not only did these fortifications increase the amount of artillery required to blast down the walls of the cities (an expensive cost), they also increased the cost to attackers attempting to overcome the city's fortifications by scaling the walls. As Geoffrey Parker explains,

> the proliferation of artillery fortresses escalated the cost of war in two crucial respects: by increasing the longevity (and decreasing the gains) of each military operation, and by driving up the number of troops and the amount of equipment required to fight wars.[28]

The winners and losers were, as Italian political theorist of the era Giovanni Botero noted, those able 'not to smash but to tire; not to defeat but to wear down the enemy. This form of warfare is entirely dependent on money'.[29]

But the *trace italienne* was itself extraordinarily expensive, a vulnerability which threatened states adopting the RMA.[30] As Geoffrey Parker recounts, when the Republic of Siena embarked on a new fortification construction in 1553, 'labour, funds, and building materials for such a major project were all so hard to come by' that the Republic was left both half-done with its fortifications and broke when enemies invaded in 1554. Unfortunately for Siena, 'the Republic had spent so much on fortification that it had no resources left either to raise a relief army or even to hire and man a fleet to succor its coastal fortresses'. The Republic capitulated to invaders and was ultimately annexed by Florence.[31]

For centuries, monarchies struggled to balance the rising economic cost of fortification warfare and the political risk of generating revenue for this warfare – with knock down effects that limited the size of conflicts. However, the rise of revolutionary armies of conscripted forces paired with the technological advancements of the telegraph, the railroad, and the rifle greatly expanded the extent of warfare and the existential cost to nations.[32]

[28]Parker, 'The Gunpowder Revolution', 111.
[29]Ibid, 111.
[30]John Lynn, 'Food, Funds, and Fortresses: Resource Mobilization and Positional Warfare in the Campaigns of Louis XIV', in *Feeding Mars* (New York, NY: Routledge, 2019) 137–159; John A. Lynn, 'The Trace Italienne and the Growth of Armies: The French Case 1', in *The Military Revolution Debate*, 169–200; John Landers, 'The Destructiveness of Pre-Industrial Warfare: Political and Technological Determinants', *Journal of Peace Research* 42/4 (2005), 455–470.
[31]Parker, *The Military Revolution*, 12.
[32]Knox and Murray, *The Dynamics of Military Revolution 1300–2050;* Parker, *The Cambridge History of Warfare*; Simon Paul Mackenzie, *Revolutionary Armies in the Modern Era: A Revisionist Approach* (New York: Routledge 2013).

Whereas before, regimes bore much of the political risk for the economic cost of warfare, now the new nation state's very existence was threatened by the scale of conflict. This is because the rise of conscription and large armies created enormous power for states able to harness their populations, but also made these nation-states vulnerable when nationalist sentiments turned against the regime or when outsiders fomented internal dissent.

In order to survive in this era of large armies and deadlier, longer range fires states needed to both muster massive manpower and maintain the extraordinary economic cost of moving, supplying, and paying for these large citizen armies. As Barry Posen recounts, 'The development of the mass army depended physically on a general increase in population and wealth, so that society could provide from its surplus the reserves of manpower, weapons and supplies necessary to its effectiveness' as well as an ability to inculcate the forces with nationalist loyalty so that they could be trusted to conduct the dispersal tactics that mitigated the era's advances in firing power'.[33]

Ultimately, despite tactical and operational successes by military geniuses of the era, the states best able to adopt technologies that changed economic cost persevered. Britain, for example, 'possessed the most rational and effective system of war finance in Europe',[34] while Union victory in the American Civil War was in large part because, 'Each time Grant turned the Confederate flank . . . he relied on the Federal government's ability to pay for the ships and cargo required . . . the North alone discovered how to mobilize its material resources without ruinous political and economic consequences'.[35]

Even Prussia's edge against France was not necessarily in the adoption of the needle gun but instead in how they used railroads and telegraphs.[36] Unlike post-Napoleonic France, Prussia could not rely on the expensive and politically fraught large standing armies; instead turning to technology to enable a predominantly civilian reserve force to compete with large standing armies – building railroads to buy time and using the telegraph to quickly issue mobilization orders. As Showalter concludes, the Prussian war ministry's ultimate success was in 'organizing

[33]Barry Posen, 'Nationalism, the Mass Army, and Military Power', *International Security* 18/2 (1993), 83–84. For more on the role of economic cost and raising large armies, see Jean Paul Bertaud, *The army of the French Revolution* (Princeton: Princeton University Press 2019); Owen Connelly, *The Wars of the French Revolution and Napoleon, 1792–1815* (New York, NY: Routledge 2012).

[34]John A. Lynn, 'Nation in Arms', in (ed.), Geoffrey Parker, *The Cambridge History of Warfare*, 215.

[35]Mark Grimsley, 'Surviving Military Revolution: The U.S. Civil War', in (eds.), Macgregor Knox and Williamson Murray, *The Dynamics of Military Revolution 1300–2050*, 84.

[36]Dennis E. Showalter, 'The Prusso-German RMA, 1840–1871', in (eds.), Macgregor Knox and Williamson Murray, *The Dynamics of Military Revolution 1300–2050*, 92–113; Geoffrey Warwo, *The Austro-Prussian War: Austria's War with Prussia and Italy in 1866* (Cambridge: Cambridge University Press 1997); Geoffrey Herrera, 'Inventing the Railroad and Rifle Revolution: Information, Military Innovation and the Rise of Germany', *Journal of Strategic Studies* 27/2 (2004), 243–271; Dennis E. Showalter, 'The Retaming of Bellona: Prussia and the Institutionalization of the Napoleonic Legacy, 1815–1876', *The Journal of Military History* 44/2 (1980), 57.

the most efficient use of Prussia's limited resources for the great number of contingencies without destabilizing the society that the army existed to serve'.[37]

Technology's relationship with the economic and political cost of warfare continued into the twentieth century. As radios and artillery increased the range of fire and machine guns and bolt-action rifles introduced devastating firepower, there seemed at first to be a real opportunity for technology to create overwhelming advantages for early adopter states.[38] However, as advances in defensive capabilities limited the strategic impact of artillery, war quickly stymied along miles of trench lines. World War I became a case study in bloody impasse – how technology improvements in lethality couldn't, alone, turn into strategic success. Ultimately, it was the Allies' ability to garner more men and material in the *materialshlacht* (or battle of resources) which doomed the German forces.[39]

Decades later, World War II introduced a series of revolutions in military affairs – including the rise of aviation, naval carriers, and combined fast maneuver tactics (blitzkrieg). Advances in airpower, radars, radios, and mechanized capabilities made modern militaries more maneuverable and extended the edges of the battlefield.[40] However, despite these RMAs, it was the ability for the allies to sustain conflict against a strapped Germany and the introduction of mass firepower via nuclear weapons in the Pacific that would ultimately lead to strategic outcomes.

Autonomous systems: Where are we now

This brings us to what many call the information revolution – a series of technological innovations including the microprocessor and internet, which increased the precision, range, and speed of modern warfare.[41] Autonomous technology is part of this revolution, a genre of systems – to include platforms and munitions – that have some ability to accomplish their mission without direct human intervention. That autonomy varies in a series of ways.[42] First, in its function: operating a machine, navigating an environment, collecting information, making decisions about employing weapons, or tracking targets.

[37]Showalter, 'The Prusso-German RMA, 1840–1871', 105.

[38]Murray and Millett, (eds.), *Military Innovation in the Interwar Period*; John Ellis, *The Social History of the Machine Gun* (Baltimore: JHU Press 1986).

[39]Williamson Murray, 'The West at War', in *The Cambridge History of Warfare*, 305; Barry Dysart (Materialschlacht: The Materiel Battle in the European Theater), *The Big L: American Logistics in World War II* (1997).

[40]Millett and Murray. 'Military effectiveness'.

[41]Robert Keohane, and Joseph S. Nye Jr., 'Power and Interdependence in the Information Age', *Foreign Affairs* 77 (1998), 81; Jessica Mathews, 'The Information Revolution', *Foreign Policy* 119 (2000), 63–65; Steven Metz, *Armed Conflict in the 21st Century: The Information Revolution and Post-Modern Warfare* (Carlisle Barracks: Strategic Studies Institute 2000).

[42]Paul Scharre, *Army of None (*New York, NY: W.W. Norton Company 2018).

Secondly, in levels of autonomy – from those completely autonomous in both operations and employment to systems partially autonomous or remotely operated. Some autonomous platforms return after missions, but the genre also includes platforms and munitions designed for single use. Examples of autonomous platforms include those used for reconnaissance – listening stations, satellites, unmanned aerial vehicles – but also systems for logistics, communications, and strike. Some autonomous systems operate far from the initial manned hand-off, even across the globe. Others have much shorter tethers, within line of sight of a manned unit or platform. Some are large and expensive while others are small and cheap. On the ground, they can be as small as trunk size robots or as large as unmanned transport vehicles. In the sea, autonomous systems operate underwater and, on the surface, sometimes as unsophisticated as dumb mines and other times as complex as unmanned surface vehicles. They include missiles, robots, aircraft, ships, submarines, and satellites, giving defense practitioners a wide array of capabilities from which to experiment.

Over the years, this diversity in autonomous technology has led to a few dominant trajectories – missiles and rockets designed for single use strike, completely autonomous intelligence platforms, and (only recently) armed remote-controlled airborne platforms. These dominant trajectories are the product of constant experimentation about the revolutionary nature of autonomous technologies. This experimentation started in earnest during the Cold War as autonomous systems transitioned from experimental to an operational part of the force. Microprocessors, space-capable rockets, and new camera and sensor technology created new missions for autonomous systems. In this time period, rockets, missiles, and satellites dominated. Unmanned aircraft, designed to be used multiple times required sophisticated control mechanisms while rockets and missiles were comparatively simpler, with no logistical tail. Meanwhile, satellites were a low cost/low risk alternative to high cost long-range unmanned reconnaissance aircraft and so most autonomous aircraft experimentation occurred at the tactical (vice strategic level). Leading up to Vietnam, the US' autonomous systems were focused on strategic missions, including long-range nuclear strike and space-based intelligence.

Vietnam was a pivotal turning point for US autonomous systems. As the 'limited' war in Vietnam expanded and became less politically tenable, political decision makers and campaign commanders needed unmanned options to reduce US casualty counts and provide much needed (and otherwise dangerous) combat reconnaissance. This included an ambitious project pioneered by Westmoreland to create an 'invisible fence' of unmanned surveillance in Vietnam that was designed to call for autonomous strike.[43] The Air Force also

[43] Andrew Cockburn, *Kill Chain: The Rise of the High-Tech Assassins* (London: Picador Books 2015); Thomas Mahnken, *Technology and the American Way of War* (New York: Columbia University Press 2008).

fielded its first operational unmanned tactical reconnaissance systems. The Lightning Bug and later Buffalo Hunter drones few over 4,000 sorties in Vietnam, serving as bait for manned missions, taking photos of Vietnamese surface-to-air missiles, and conducting poor weather battle damage assessments.[44]

Although this initial foray was mostly characterized by novelty successes, the lessons of Vietnam proved foundational to the investment and adoption of autonomous systems in subsequent decades,[45] particularly in incentivizing investment in autonomous systems that mitigated political risk. Even as the US was reeling from losses in Vietnam, the rise of digital technology unlocked the ability to collect, store, and transmit large packets of digital information. Campaigns in Iraq, Somalia, and Bosnia became proving grounds for unmanned aerial vehicles and cruise missiles, where they struck from increasingly long distances, and provided risk-free, persistent, and immediate intelligence.

Meanwhile, the increasingly high cost of satellite reconnaissance and coverage limitations created a desire for tactical unmanned aerial vehicles, able to provide persistent coverage over targets, increasingly with real time video download capability. The advent of wireless network technologies that could transmit both within line of sight and (with satellite relay) over the horizon made it possible for the newly developed MQ-1 remotely-controlled Predator airplane[46] to transmit videos to field and combatant commanders, who were intent to avoid the political ramifications of nasty public debacles like Somalia.[47] 9/11 created the impetus to arm what had been a reconnaissance only unmanned system, thereby introducing to the battlefield one of the first armed unmanned platforms (there had been many other semi-autonomous munitions). Not surprisingly, unmanned investment post-9/11 was heavily focused on platforms within the air domain. The MQ-1 and its successor the MQ-9 became integral to campaigns in Iraq and Afghanistan, both for persistent reconnaissance and (increasingly) strike missions. Further, a long-range reconnaissance air platform, the Global Hawk (meant to replace the manned U-2) also debuted in the decade after 9/11 to provide high altitude, long-range intelligence coverage.

By fiscal year 2020, National Defense Authorization Act authorized over $10 billion dollars for autonomous systems, including $3.1 billion for unmanned platforms, $6 billion for missiles, and $1.3 billion for space

[44]Erhard, *Air Force UAVs*.

[45]Mahnken, *Technology and The American Way of War Since 1945*, 112; Alice Hunt Friend, 'Creating Requirements: Emerging Military Capabilities, Civilian Preferences, and Civil-Military Relations', PhD dissertation, American Univ., 2020.

[46]Richard Whittle, *Predator: The Secret Origins of the Drone Revolution* (New York: Henry Holt and Company 2014).

[47]Ibid.

systems. And while this is probably only a portion of the total outlays for classified systems, cumulatively they made up 1.5% of the FY 2020 budget.[48] Almost all of the unmanned platforms in this authorization are not truly autonomous, and instead require remote control, either from line of sight or via satellite across the horizon. Missiles also continue to be a large portion of the unmanned inventory, especially air to ground missiles, air to air missiles, and intercontinental ballistic missiles. Additionally, the naval domain includes investments in underwater drones, including systems that specialize in mine countermeasures, identification, or disposal (Sea Fox, Barracuda, Mk18, etc.) as well as underwater and surface intelligence (Sea Stalker, Sea Maverick, etc.). A large part of the Navy's investment in unmanned technology is in munitions, and, in particular, updates to submarine launched ballistic missiles. Further, by 2021, the budget called for significant investments in unmanned surface ships – part of the Navy's larger strategy to increase the size of the Navy by augmenting manned platforms with unmanned.[49] Finally, the ground domain lagged the other domains. While the Army invested in unmanned aerial systems for tactical reconnaissance, it did not invest similar resources in the ground domain. Investments in unmanned ground systems have been mostly in explosive ordnance disposal as well as recent investments in testing unmanned combat vehicles.

Autonomous systems –applying lessons from historical revolutions

This wide range of autonomous technologies illustrates how difficult is to assess, let alone, confirm the 'revolutionary' benefits of autonomy. Absent a clear theory of revolutionary effects, investments in autonomy largely focusing on creating three battlefield characteristics: 1) speed, 2) range, and 3) persistence/precision. We argue that, based on our analysis of historical revolutions, RMAs may occur within each of these characteristics but that it is only acquisition strategies that maximize economic and to some extent political cost that lead to revolutionary effects on military power. So how do these characteristics create battlefield effectiveness – and which investments are most likely to lead to decreases in political or economic cost?

For many – especially those viewing autonomy through the lens of the information revolution – the revolutionary effect of autonomy is to create speed, dramatically improving battlefield effectiveness and strategic success by decreasing the time required to respond to and engage

[48]National Defense Authorization Act for Fiscal Year 2020, S.1790, 116th Congress (2019).
[49]Ronald O' Rourke, *Navy Large Unmanned Surface and Undersea Vehicle: Background and Issues for Congress* (Washington: U.S. Library of Congress, Congressional Research Service, RL45757 2020).

threats.[50] As Krepinevich outlines, this new revolution includes 'the use of space platforms, unmanned air-breathing aircraft, high-speed computers, and a variety of sensors to gather, process, and move huge amounts of relevant information'[51] with systems increasingly automated 'to gain/maintain information dominance by minimizing the expenditure of time'.[52] Accordingly, these investments privilege full autonomy over partial human control and focus on the proliferation of autonomous systems, all networked together with centralized processing centers. At its penultimate, these autonomous technologies maximize speed by putting the sensor and the shooter on the same autonomous platform – able to make decisions about targeting without human intervention.

Speed creates operational and tactical advantage, which can be decisive in short wars of coercion. However, investments in autonomous technologies for speed come with trade-offs. First, autonomous technologies maximized for speed sacrifice control, relying on machine automation to decrease engagement time, thus increasing the chance for accidents and inadvertent escalation. Additionally, in order to decrease engagement time, autonomous technologies designed to increase speed are dependent on complicated networks and datalinks. This can lead to cumbersome and expensive acquisition programs (for example the Army's Future Combat System[53]) as well as dependence on what have been fragile and complex networks[54] with novel vulnerabilities to network interference and failure – especially in contested environments.[55] A solution is mass autonomy, using large amounts of autonomous technologies as communications relays and sensors, in order to create mesh, distributed networks more resilient to jamming, cyber, or kinetic attacks. However, in order to sustain the quantity required for resilience, these systems must be low in cost, allowing the military to lose and replace portions of the autonomous network at a lower cost than the munitions attacking the autonomous nodes.

[50]Krepinevich, Jr., 'The Military-Technical Revolution: A Preliminary Assessment', Cohen, 'A revolution in warfare', Metz, *Armed Conflict in the 21st Century: The Information Revolution and Post-Modern Warfare*.; Nye and Owens, 'America's Information Edge'; Dave Deptula and Mike Francisco, 'Air Force ISR operations: Hunting versus Gathering', *Air & Space Power Journal* 24/4 (2010), 13–18; David Deptula, *Unmanned Aircraft Systems Taking Strategy to Task* (Washington, DC: National Defense University 2008); Antoine J. Bosquet, *The Scientific Way of Warfare: Order and Chaos on the Battlefields of Modernity* (Oxford University Press, 2022).

[51]Ibid, 15.

[52]Ibid, 15.

[53]Christopher G. Pernin et al, *Lessons from the Army's Future Combat Systems Program* (Santa Monica: RAND Corporation 2012).

[54]Andrew Eversden, 'Networks as Center of Gravity: Project Convergence Highlights Military's New Battle with Bandwidth', *Breakingdefense.com*, November 23, 2021.

[55]Jacquelyn Schneider, 'The Capability/Vulnerability Paradox and Military Revolutions: Implications for Computing, Cyber, and the Onset of War', *Journal of Strategic Studies* 42/6 (2019), 841–863.

A related argument is that the real revolution of autonomous systems is the ability to remove the human from the battlefield, thus increasing the ability to see and target from further and further away. This ultimately creates revolutionary advantages in two related characteristics of warfare: range for first strike and force protection.[56] This argument works slightly differently than speed, which is tied to decisional awareness and quick response but is largely agnostic to geographic space or even ability to shield personnel from danger. Instead, range allows the employing force to extend the distance from the battlefield, creating surprise and insulating personnel (and ultimately decisionmakers) from risk and political cost (especially for wars of coercion) by giving foreign policy decisionmakers a less escalatory option in crises.[57] Range is therefore highly advantageous for opportunistic strikes of coercion, for maximizing surprise, and for conducting campaigns without the need to rally domestic support.

Both speed and range create first strike incentives and privilege offensive campaigns – speed because of its focus on quick and decisive campaigns and range because of its ability to keep war far from an offensive country's borders. However, autonomous technologies that privilege range come with trade-offs, particularly for economic cost. For example, in order to create range, a system generally needs more powerful propulsion and more fuel: two factors that increase the cost of the platform. Further, in order to maintain control over long-ranges, systems need sophisticated targeting networks and guidance systems and, potentially, remote control. Remote controlled systems, especially ones that must operate with a satellite relay, have a higher logistical tail cost than strictly autonomous systems. Similarly, these platforms are much higher cost to maintain and operate than munitions, though increasingly smart and autonomous munitions used to maximize range and long-range strike have ballooned in cost. The AIM-120d missile, for example, costs more than $2 million while a single Tomahawk missile comes in between $1–1.8 million. The main cost here is in the guidance systems which make the missiles more survivable and more responsive to last minute changes in targeting (generated from integrated sensor networks and mass processing centers).

A third argument is that autonomy allows systems to loiter persistently, generating revolutionary advantages in precision. Arguments about the revolutionary effects of precision warfare go back to Gulf War debates about centers of gravity and effects-based operations, but extend to counter-

[56]David Deptula, 'Long Range Strike More Potent, More Survivable, Cheaper', *Breaking Defense*, January 2017. https://breakingdefense.com/2017/01/long-range-strike-more-potent-more-survivable-cheaper/.

[57]Erik Lin-Greenberg, 'Wargame of Drones: Remotely Piloted Aircraft and Crisis Escalation', *Journal of Conflict Resolution* (2022).

terrorism decapitation tactics.[58] According to this logic, the ability to precisely target allows states to achieve strategic success with limited use of force, thus insulating human losses and ensuring public support for long campaigns.[59] Autonomous systems provide this precision in two ways. On one hand, unmanned systems can loiter for extended mission times, providing near real time situational awareness. They do so by negating the physiological limitations of a manned aircraft. For example, unmanned air platforms like the MQ-9 boast longer loiter times by offering the remotely-based crew the ability to swap out mid-mission, or even to perform simple tasks to mitigate physical fatigue (bathroom, coffee, stretching, lunch breaks). Fully autonomous platforms, especially those with no need to refuel, can significantly increase loiter time for intelligence collection (for examples, satellites or underwater detection systems) while providing precise targeting information that decreases the need for close-range munitions employment. Like range and force protection, precision and persistence require significant logistical cost and, like speed, rely on networks and sensors. This means that systems designed for persistence that don't trade off control or survivability come at high cost, making them scarcer on the battlefield. This scarcity, in turn, creates fragility within networks reliant on few but exquisite autonomous systems.

What does all this mean for autonomy and cost – both political and economic? The cost of autonomous technologies is not fixed, instead it is contingent on the battlefield characteristics and theories of victory for which it is built. If the theory of victory is speed, then the focus is on autonomous unmanned systems with advanced and resilient networks. That technology may be expensive and exquisite, but these exquisite autonomous options might also have a cheaper logistical or operational tail. In contrast, if the focus is on precision and force protection, then expensive sensors, data relays, and remote crews will significantly drive up both the cost of the platform and the operational costs but may significantly limit the political cost of force. In general, as autonomous systems are called on to mitigate more political cost, they become more expensive. Cheap autonomy requires delegation to the machine and inherently limits control – a consideration which may not affect already bloody conflict but which can lead to accidents and inadvertent escalation in carefully calculated wars of coercion.

[58] John Andreas Olsen, *John Warden and the Renaissance of American Air Power* (Washington: Potomac Books 1997); Thomas A. Keaney and Eliot A. Cohen, *Gulf War Air Power Survey: Weapons, Tactics, and Training and Space Operations* (4: Office of the Secretary of the Air Force 1993); John Warden, *The Air Campaign: Planning for Combat* iUniverse, 1998; David Deptula, 'Effects-based Operations', *Air and Space Power Journal* 20/1 (2006): 4; Patrick B. Johnstone, 'Does Decapitation Work? Assessing the Effectiveness of Leadership Targeting in Counterinsurgency Campaign', *International Security* 36/4 (2012), 47–79.

[59] James Igoe Walsh, 'Precision Weapons, Civilian Casualties, and Support for the Use of Force', *Political Psychology* 36/5 (2015), 507–523; Jacquelyn Schneider and Julia Macdonald, 'US Public Support for Drone Strikes' (Washington, DC: Center for New American Security 2016).

Conclusion: Towards revolutionary autonomous warfare

While much of the autonomy discussion focuses on range, speed, or precision – these are generally tactical or operational characteristics that may create smaller revolutions in military affairs, but do not necessarily create the kind of strategic successes that revolutionize military power. Instead, if states want autonomy to catalyze a military revolution, they will need to build systems that create advantages in political and economic cost. This leads to two acquisition strategies to optimize autonomous weapons. First, in low stakes warfare or 'competition' short of conflict – scenarios concerned about achieving coercive aims without escalation – autonomous systems should privilege political cost by focusing on control, precision, persistence, and range. This means investing in unmanned strike technologies with sophisticated sensors, guidance, and potentially remote operations by human controllers. Mass and quantity are less important in this strategy, barring extended low-scale conflict with heavy attrition.

In contrast, in great power conflict, autonomous systems that privilege political cost may have little utility beyond the initial stages of a crisis. Instead, these systems must be designed to decrease economic cost. This will be complicated: economic cost includes not only the platform or munition, but also the logistical tail, information technology, and the manpower required to use and maintain the systems. Autonomy arsenals will have to balance these costs with operational trade-offs. For instance, sophisticated guidance or network support increases the effectiveness of an autonomous platform, but at an increased cost. Alternatively, autonomy is potentially cheapest without a man in the loop, but this sacrifices significant control and safety. This means that autonomy may be best optimized for missions that decrease the overall cost of warfare, but potentially not ones that substitute for manned missions. Instead, they work best as cost-saving complements to manned missions – as ways to slow down and increase the economic cost of warfare for the adversary. Instead of, for example, dog-fighting autonomous fighter jets, it would be better to use semi-autonomous drones or missiles to deplete adversary missile inventories. Instead of one autonomous resource providing total sensor coverage of an area, the development of masses of cheap, replaceable autonomous sensors with smaller, overlapping coverage. Instead of using autonomy for speed and first strike, investing in low-cost autonomous technologies to create friction and confusion.

Notably, building survivable autonomous systems is potentially counterproductive for these objectives. Survivability comes at a high economic cost; systems require control mechanisms to return after launch, smart guidance systems to accomplish their mission, sensors to detect attacks, and evasion measures to defeat incoming threats. Too much investment in survivability creates expensive (and often scarce) systems that must be defended – even requiring the protection of manned resources. Counterintuitively, the quest for survivability can turn autonomous technologies into politically sensitive resources, no longer able to mitigate either political or economic cost. To be revolutionary, autonomous technologies need not avoid detection and survive, but instead create economies of scale through large numbers of lower cost systems, complementing manned, exquisite performance by creating mass and enabling saturation tactics. The key to sustaining this kind of warfare is decreasing both the system cost and the logistical cost – both of which will be dependent on resilient networks, able to adapt when losing autonomous nodes.

Finally, our analysis reveals a limitation in the RMA literature. Much of this literature focused on how technology and organizational adaptation could create significant changes in battlefield effectiveness. However, it largely ignored both the stakes of these conflicts and the economic cost of using these technologies and tactics over time. This led to theories that could explain tactical or even short-term operational effectiveness, but by overlooking cost, fell short of strategic or revolutionary changes in military power. The power of this narrative influenced US acquisition strategies, creating incentives over the last twenty plus years to build an arsenal of autonomous systems for offensive, first strike, and quick campaigns. Perhaps unintentionally, this has led to scarce, relatively high cost, high control autonomous systems. But what our analysis shows is that the truly best use of unmanned systems is using these systems to decrease the overall economic cost of war by creating cheap, mostly automated, and ubiquitous systems. The military revolution narrative has persevered over decades of changes in American defense thinking and has led to some of the most innovative technologies in the US inventory, but as it looks to the future, scholars should look again to the past and examine how the inclusion of cost changes the implications of military revolution for defense acquisition strategies.

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