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ADAPTIVE AIRPOWER: ARMING AMERICA FOR THE FUTURE THROUGH 4D PRINTING

by

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Abstract

The author poses Seven Postulations of the future security environment in the coming decades. These Postulations give rise to the conclusion that to retain American airpower dominance into the future, the United States must lead the world in developing military operational 4D Printing capability and capacity. 4D Printing is an additive manufacturing technology that allows designer nanoscale manipulation during production to create products capable of on-demand adaptation. The Seven Postulations consider the potential strategic ramifications of globalization and technology advances over the next twenty-five years. These postulations describe a future strategic setting where uncertainty, instability, and information ubiquity fuses with technology breakthroughs to create an environment where a nation's military must continually adapt amidst a growing number of threats. In this future, strategic airpower dominance will be attained by the air force with a robust military-industrial infrastructure that can create tailored weapons to attack fleeting enemy vulnerabilities, while also protecting friendly force vulnerabilities. The USAF and the US military must invest in 4D Printing to bolster infrastructure and posture American airpower for continued dominance into the future.

Introduction

The year is 2040; people still do not own flying cars, oil is still the key global energy resource, and U.S. Air Force is still flying B-52s. However, over the past 25 years there has been a revolution in American military engineering, design, and manufacturing (EDM)—the revolution is 4D Printing. The Air Force now operates over 1000 different specialty aircraft and thousands more prototype aircraft, creating the most robust, layered, and globally capable Air Force in history—despite the increased global instability and transnational unrest. Total development costs of this revolutionized Air Force are less than the sequestration budgets of 2015, because 4D Printing changed the acquisition paradigm of burdensome manufacturing overhead, decades long phased development, and economies of scale. By transitioning to 4D Printing at the industrial level and throughout the defense enterprise, the USAF has denied adversaries the ability to gain significant military benefit by cybertheft, because hardware can be continuously improved at the small batch level. The USAF now can produce aircraft capable of adapting to their environment and dominating the newest warfighting domain—the Nano-Dimension.

4D Printing is an additive manufacturing technology that allows nanoscale manipulation and programming during the production process to ultimately create products designed to adapt to their environment.[1] While still an emerging technology and process, 4D Printing is based on current capabilities, and is poised to revolutionize much of the world's EDM over the next twenty-five years. 4D Printing is a game-changer for airpower technology, but the United States must purposefully invest in this technology and EDM infrastructure to both exploit the benefits and prepare for 4D Printing adversaries. Ultimately, to retain national airpower dominance (and by extension, American hegemony) into the future, the United States must lead the world in developing operational 4D Printing capability and capacity.

Description of 4D Printing

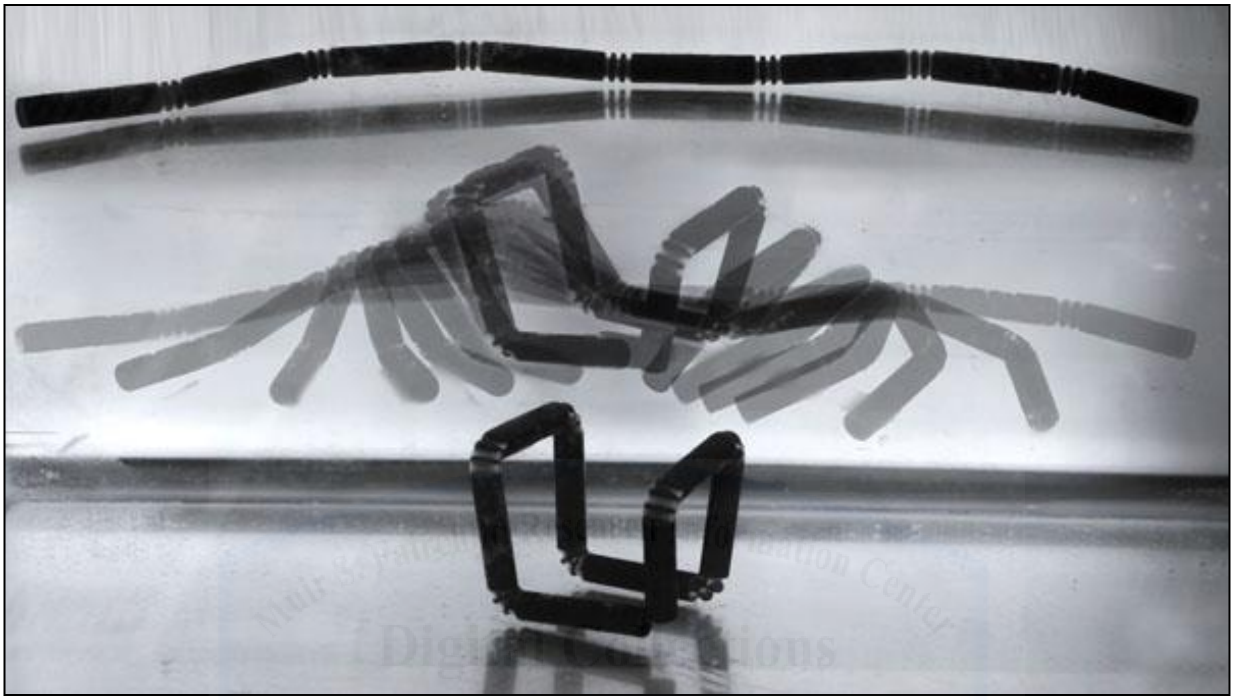

Figure 1. 4D Printed Cube Adaptation.[2]

The first (top) phase shows the 4D printed material in a structurally rigid line. The second phase shows the linear material self-assembling after exposure to a specific environment (in this case, water). The final phase shows the material in its completed cube shape.

4D Printing is the technological triptych of additive manufacturing, nanotechnology, and geometric programming. From flight suits that self-adapt during times of increased g-forces, to adaptable aircraft struts, to nanotechnology munitions, the applications for 4D Printing intersect multiple disciplines and myriad applications. Skylar Tibbits, one of the 4D Printing industry pioneers, defines 4D Printing as creating “multi-material prints with the capability to transform over time, or a customized material that can change from one shape to another, directly off the print bed.”[3] Essentially, 4D Printing combines the field of “programmable matter” with the additive manufacturing capabilities of 3D Printing to generate products in the fourth dimension—time.[4] Per Tibbits, "at the core of this technology are three key capabilities: the machine, the material, and the geometric 'programme.'"[5]

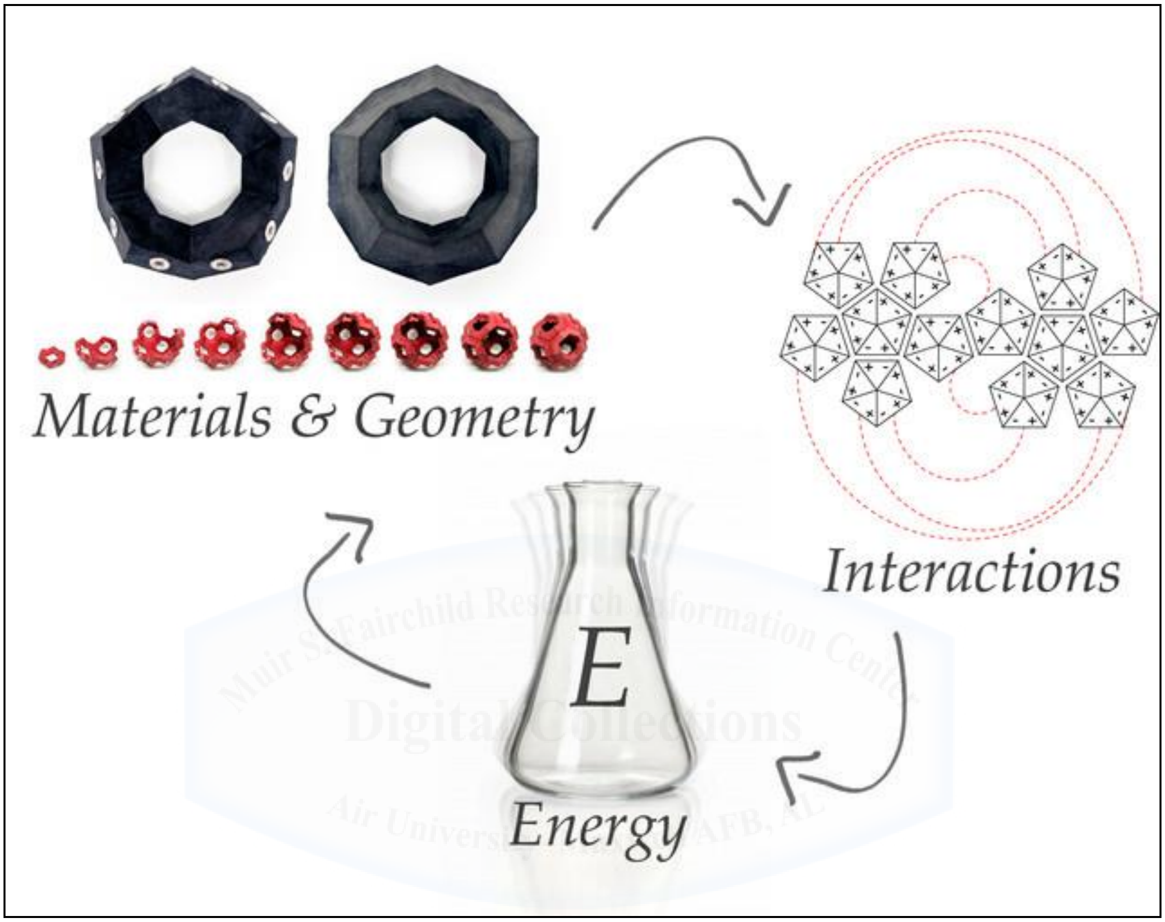

Figure 2. Three Core Components Enabling Adaptation in 4D Printed Products.[6]
Specialized materials are mathematically encoded at the molecular or nanoscale level to react to selected environments (e.g., time, water, oxygen, etc.). After production, the 4D Printed product interacts with its environment. This interaction produces positive and negative attractions within the material as it begins to self-assemble. The proper amount of energy fuels the interactions. All three of these components enable product adaptation and self-assembly.[7]

Although likely to be developed specifically for 4D application, 4D Printing machines are based on modern 3D Printing and additive manufacturing technology.[8] 3D Printers that simultaneously drive down costs while enabling intricate and improved designs are being used throughout the global economy to improve commercial aviation and automotive components, create new foods and chocolates, and even design custom fashion and lingerie.[9] 4D Printing harnesses this rapidly growing 3D industrial base. Early generation 3D Printing focused on moldable plastics and polymers, but because of the sub-molecular scale of the latest 3D commercial printers, hybrid raw and synthetic materials can be intertwined and layered down to objects as small as 285 micrometers.[10,11] Recent advances in experimental stereolithography are poised to enable additive manufacturing even down to the Nano-Dimension (between 1 to 100 nanometers).[12] As this technology matures, the capability to engineer, design, and additively manufacture nanometer-sized materials poses nearly limitless possibilities of creating custom materials for specific applications by using old, new, or blended materials. Twenty-five years from now, 4D Printing could conceivably be used to create shape-shifting micro-drones, capable of adapting their physical properties and dimensions based on received radar energy to retain stealth against any frequency of radar.

Geometric programming is the key ingredient for enabling post-production adaptation of 4D Printed products. Geometric programming, as an integrated mathematic and material approach to purposefully designing environmental reactions into the physical hardware of products, aims "to inexpensively produce millimeter-scale units that integrate computing, sensing, actuation, and locomotion mechanisms."[13] Claytronics, an industry leader in programmable matter, states that their programmable matter ambition is "to achieve synthetic reality," which envisions physical realization of all computer-generated products—including products designed to evolve with their environment.[14] Through geometric programming, in the coming decades 4D Printing could produce aircraft capable of physically adapting to their environment autonomously without the complications and vulnerabilities of software—creating what Self-Assembly Labs refers to as "robots without robots."[15]

The Seven Postulations of the Future Security Environment

Each of the following Seven Postulations gives rise to the conclusion that the US military-industrial complex must lead the world in developing operational 4D Printing to retain America's asymmetric airpower advantage. While strategic postulations of this sort cannot be neatly proven or disproven per se, they are nonetheless foundational to defense spending. Taxpayer funds invested today in national defense projects are, at their core, based on little more than hopeful extrapolations and collective perceptions of the future. To persuade the reader of this paper's thesis, these necessary extrapolations and perceptions are explained and defended. Trying to develop particular airpower solutions for a specific form of future war is akin to what journalist and author Dan Gardner calls "predicting the future by projecting the present,"[16] and it ultimately exposes America to unforeseen risk. Therefore, to hedge against future uncertainty, US airpower must be postured to agilely respond to a wide variety of threats. In this *Boydian*[17] vein of acknowledging the inherent uncertainty of the future, these following Seven Postulations humbly contain purposeful ambiguity, while also characterizing the future in a manner that highlights strategic changes and the concomitant attributes required for retaining military dominance. The common thread between all Seven Postulations is the strategic imperative for the United States to lead the world in operationalized 4D Printing to retain airpower dominance.

Postulation 1 – Volatile Consequences of Globalization

> *In the coming decades, globalization will cause both national and transnational instability and violence as grievances, identities, and ideologies clash. The volatile nature of globalization will further cloud and distort US ability to predict future wars. The future battlespace will grow increasingly complex and contested as globalization distributes warfighting ways and means amongst nations.*

Much has been analyzed, pontificated, and prophesied regarding both the virtues and evils of globalization. More than mere economic phenomenon, globalization is multifaceted and tends to contain clashing influences. Political strategist Zbigniew Brzezinski (National Security Advisor to President Carter) defines globalization as “a way of ordering/reordering economically and politically the world.”[18] Extending this concept, economist Malcolm Waters imagines the paradox of a globalized planet “not likely to be harmoniously integrated.”[19] Many experts foresee globalization both uniting the globe, while also causing increased unrest. Globalization often boosts living standards, but also erodes regional micro-economies, thereby threatening traditions and identities of peoples around the world.[20] Henry Kissinger characterizes the coming age of “increasingly contradictory realities” as being fueled by global technology advancements and information ubiquity.[21] During the Cold War, the military-industrial complex could focus defense projects on Soviet defeat, but in the future, accelerated globalization will create a destabilized strategic environment where crises can erupt with virtually no warning.

The ever-looming potential of national and transnational unrest in the future means that the United States should pursue a defense strategy of *layered mass*—consisting of a large quantity of purpose-built weapons. Currently, maintaining a vast and diverse aircraft fleet is likely unrealistic given budget constraints. However, a 4D Printing infrastructure is exactly the form of airpower industrial base needed to implement a cost-effective layered mass strategy. During any crisis, the proper 4D Printing infrastructure could turn defense budgets into specific air solutions to enforce national policy. Like many emerging technologies, the potential of 4D Printing is available to virtually every nation in the developed world. For example, China is well postured to capitalize on 4D Printing, and has already developed cutting edge military 3D Printed maps and other 3D applications.[22] In the coming age of “increasingly contradictory realities,” the nation with the most robust military-industrial 4D Printing infrastructure will possess a strategic advantage for crisis response and seizing the initiative.[23]

Postulation 2 – Rising Need for Tailored Airpower Solutions to Achieve Precision

> *As globalization strengthens global economic interconnection, US policy will require increasingly tailored airpower solutions to maximize violence on specified enemies while minimizing economic damage. Senior leaders will conceptualize precision as more than mere weapon accuracy—driving the requirement to develop customized weapon systems.*

In the future, economic globalization will tighten the interconnectivity between national economies, constraining the use of airpower. Airstrikes damaging infrastructure will have discernably negative ripple effects on the US and world economies. Strengthened economic interconnectivity is evidenced even now. In 1997, China's nationalized economy remained stable despite the Asian financial market crisis; however, in 2007, after of decade of foreign direct investment into the Chinese economy, the Wall Street subprime lending disaster triggered a 73 percent value loss within the Shanghai Index.[24] This byproduct of economic interconnectedness leads to what some economists refer to as "financial contagion"—local economic crises tend to spread like a virus.[25] The future will see this trend intensify, and both prosperity and recessions will become more widely shared. Therefore, military leaders will have to contend with the increasingly potent economic side effects of airpower. This phenomenon will naturally be juxtaposed with the desire to end conflicts quickly and safely through airpower's violence and precision—eventually evolving the military term of *precision* itself.

The strategic impact of this escalating tension will be an ever-increasing appetite for a more progressive concept of *precision*—where national leaders conceptualize precision as more than weapon accuracy. The future concept of aerial strike precision will also include new ideas like precision of domain, effects, time, intelligence, and attribution. Precision will mean more than bombs-on-target; rather, precision will mean closing the gap between desired, planned, and achieved effects. Technology advances will enable a new level of precision between these effects, but achieving this form of contextual precision in the technologically and geopolitically complex future operational environment will require tailored airpower solutions. A 4D Printing military-industrial infrastructure will enable a cost-effective layered Air Force capable of printing adaptive and customized weapon systems. These weapon systems could attack critical vulnerabilities and decisive points in a precise manner consistent with nuanced national policies.

Postulation 3 – Decisiveness of Rapidly Fielding New Technology

> *The global development of potentially game-changing airpower technologies will provide a temporary asymmetric advantage to the air force best able to rapidly operationalize new technologies. This temporary advantage may become a decisive factor in future wars. Rapidly fielding these temporary technology asymmetries will require low-cost / high fidelity prototyping and operational verification freed from the traditional manufacturing limitations of economies of scale.*

In the coming decades, the unforeseen amalgamation of myriad scientific advancements will create an operational environment constantly on the brink of game-changing technological breakthroughs. Supercomputing, quantum mechanics, artificial intelligence, hybrid energy, nanotechnology, and other breakthroughs will redefine and revolutionize military superiority at an rapid pace in comparison to the 20th Century. These advances will pose tremendous opportunities to increase US airpower superiority, but they will also post grave threats to American military forces. The globalization of technology will cause a wide distribution of access to these breakthroughs throughout the world. Additionally, the information ubiquity of the future will both increase the number of these breakthroughs while decreasing the effective time of asymmetry before countermeasures can be developed. Even now, closely guarded trade secrets are subjected to international theft and distribution, demonstrated in May of 2014 when the Department of Justice indicted five Chinese nationals on charges of cybertheft involving highly sensitive commercial data.[26] This trend will likely continue. Therefore, in future decades, much of military superiority will be gained by nations that operationalize global technology breakthroughs faster than their adversaries. Technical knowledge alone will not be militarily empowering—the source of military power in the future will be the nimble infrastructure needed to quickly weaponize technological breakthroughs.

A 4D Printing military-industrial infrastructure will posture the USAF to exploit forthcoming technology breakthroughs, creating decisive effects. As a form of additive manufacturing, 4D Printing is conceptually based on a common overhead for dissimilar products, and is particularly well suited to complex designs and materials. Without a 4D Printing industrial base, the US defense industry may still produce technology advancements, but these advancements should be assumed to be available to militaries worldwide—including adversaries. Thus, without robust US 4D Printing industrial base, US technology breakthroughs could actually fuel decisive advantages for an adversary that does possess 4D Printing infrastructure.

Postulation 4 – Vulnerability of Mass Produced Systems

> *The shrinking technological gap between the United States and its adversaries places more importance on quantity, as qualitative advantage alone will often not be decisive. However, mass-producing any particular aircraft type, regardless of its strengths, exposes the United States to the strategic risk of non-diversification—fleet-wide matching weaknesses. In the Information Age, system vulnerabilities will become increasingly difficult to conceal, requiring the USAF to differentiate its weapon systems to minimize the cloned vulnerabilities created by mass production. To dominate in the coming decades, the USAF must possess high capacity with diversified capability.*

In a future environment where information ubiquity yields decisive—yet fleeting—technology advantage, mass-produced weapons will become increasing vulnerable to fleet wide defeat. As globalization broadens the global availability of information, safeguarding the knowledge of aircraft critical vulnerabilities will become progressively difficult. Resultantly, the vulnerabilities of future aircraft and weapons systems will be widely disseminated amongst operators, allies, and even adversaries. In a world with ubiquitous access to information, mass cloning a particular weapon system or aircraft type will expose the US military to the potential for enemy exploitation of a specific mass-produced vulnerability.

Analogous to a diversified stock portfolio, a nation will gain strategic advantage in the coming decades when its military vulnerabilities are diversified, while possessing the capability and capacity to exploit common vulnerabilities in mass-produced enemy weapon systems. For example, whether the United States possesses 200 or 20,000 F-35s, if an adversary has the knowledge and means to identify the F-35's unique critical vulnerabilities and can produce a customized countermeasure, a high quantity of F-35s will not create sustainable military advantage. Over the coming decades, defense system knowledge will be disseminated. However, the possessing the means—not only the knowledge—to exploit vulnerabilities will require a robust EDM infrastructure with the scalability and intricacy required to quickly produce products designed to attack specific enemy vulnerabilities.

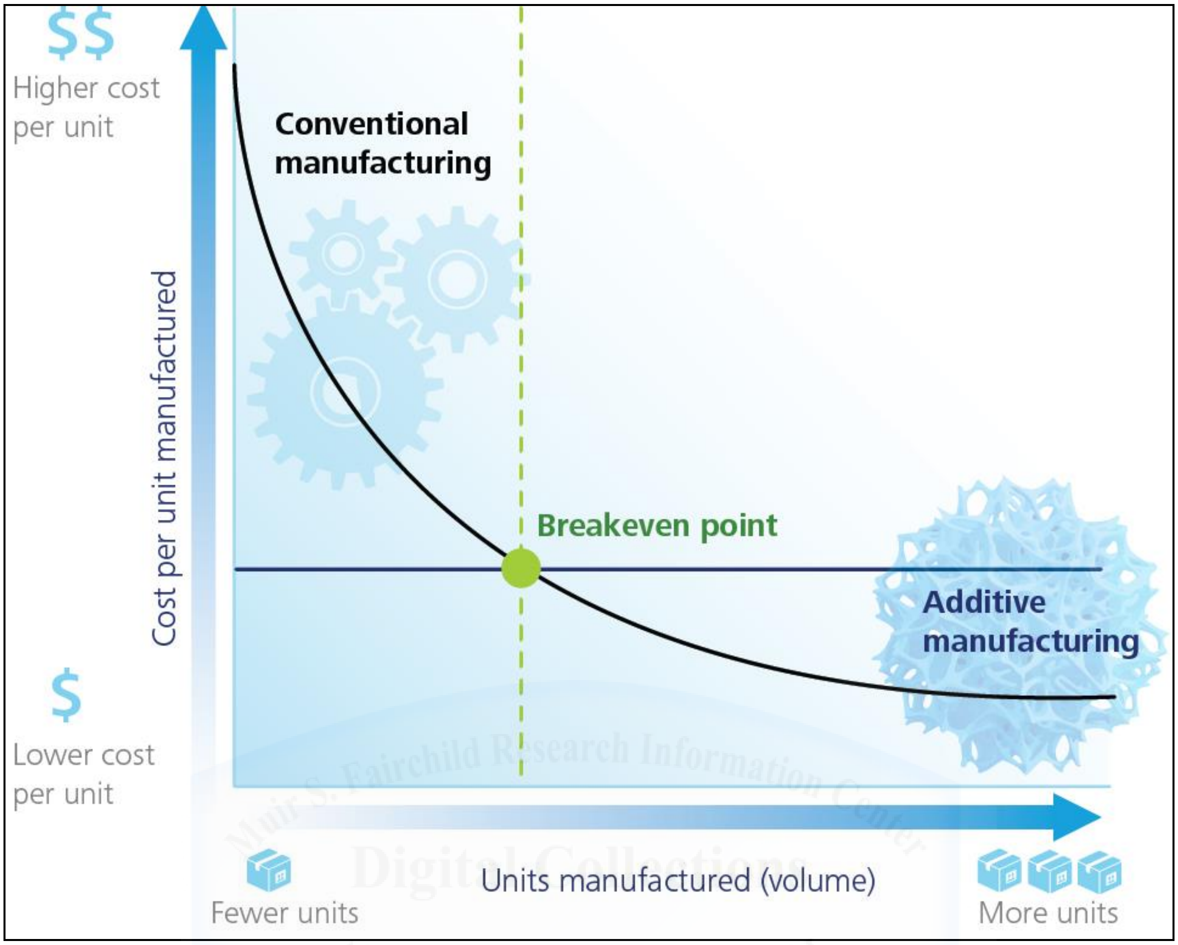

Figure 3. Cost Analysis Comparing Conventional with Additive Manufacturing.[27]
With conventional manufacturing, enough units must be produced to financially break-even and units produced beyond the break-even point contribute to profitability (depicted as the cost curve). In contrast, profitability is not directly tied to manufacturing a higher number of units in additive manufacturing. This cost trait allows additively manufactured products to achieve profitability even when produced in small quantities.

A layered mass of airpower solutions—attainable by a 4D Printing industrial base—can overlap vulnerabilities to create an integrated and more resilient Air Force. Because 4D Printing and additive manufacturing breaks the traditional economies of scale cost curve in EDM, 4D Printing would allow the US military to intersect aircraft vulnerabilities to prevent adversaries from developing a singular offensive weapon to attack cloned weaknesses. 4D Printing also provides the US military-industrial enterprise *freedom of quantity*, because the per-unit costs from additive manufacturing remain relatively stable regardless of batch size or run times.

Therefore, 4D Printing infrastructure postures the US military to quickly turn defense spending into attacks on fleeting adversary vulnerabilities.

Postulation 5 – Airpower Hardware Must be Continuously Improved

> *Consistent with history, airpower victory in the future will still require continuous and incremental application of lessons learned. However, the lessons learned must be implemented throughout weapon system hardware and software—not only operator tactics. In the future, warfighting will see a growing fusion of operator, hardware, and software.*

Future American warfighters will be tightly fused with their weapon systems, as continual advancements in computing and hardware will tightly integrate operator, hardware, and software. In the coming decades, advances in nanotechnology and artificial intelligence could create super-enabled Airmen capable of tremendous violence management during combat. These next-generation Airmen will operate weapon systems designed to augment and enhance virtually all of their human functions, as correspondingly envisioned by theorist Michio Kaku's description of the future widespread use of robotics and artificial intelligence.[28] The fusion of operator, hardware, and software will generate many clear benefits; however, this phenomenon will also redefine learning during war.

To implement lessons learned in conflicts of the future, improvements and modifications to hardware will have to accompany desired changes in tactics or strategy. Learning during war will remain essential to future success, but the distinction in the future is that nations will be dependent on their ability to quickly implement lessons learned in the battlespace by modifying their hardware along with their tactics or strategy. By increasing the dependency of the operator on combat hardware and software, much of the learning that occurs during wartime will only be able to be implemented with corresponding hardware and software modifications. Relying on conventional manufacturing to develop new weapon systems will stifle lessons learned implementation in the future. Therefore, a responsive industrial base—achievable with 4D Printing—will be required to rapidly implement tactical lessons learned. By 2040, embedding a form of adaptive intelligence directly into the structure of an aircraft could enable autonomous lessons learned implementation at the hardware level—complimenting operator and software adaptation. At its core, 4D Printing enables a military-industrial complex to institute learning and adaption into the all weapon systems, and in the future, applying wartime lessons learned will require changes to both operator actions and hardware composition.

Postulation 6 – The Nano-Dimension is the Next Domain of Warfare

> *An additional domain of warfare will be weaponized and contested in the future—the Nano-Dimension. Similar to cyber, the Nano-Dimension will powerfully impact airpower and all forms of warfare. Advances in the Nano-Dimension, to include nano-machines and molecular manipulation, will permanently change the disparate fields of molecular biology, quantum mechanics, semiconductors, supercomputing, and others. The Nano-Dimension will be weaponized, and the USAF must possess the infrastructure to harness the Nano-Dimension across virtually all applications of airpower.*

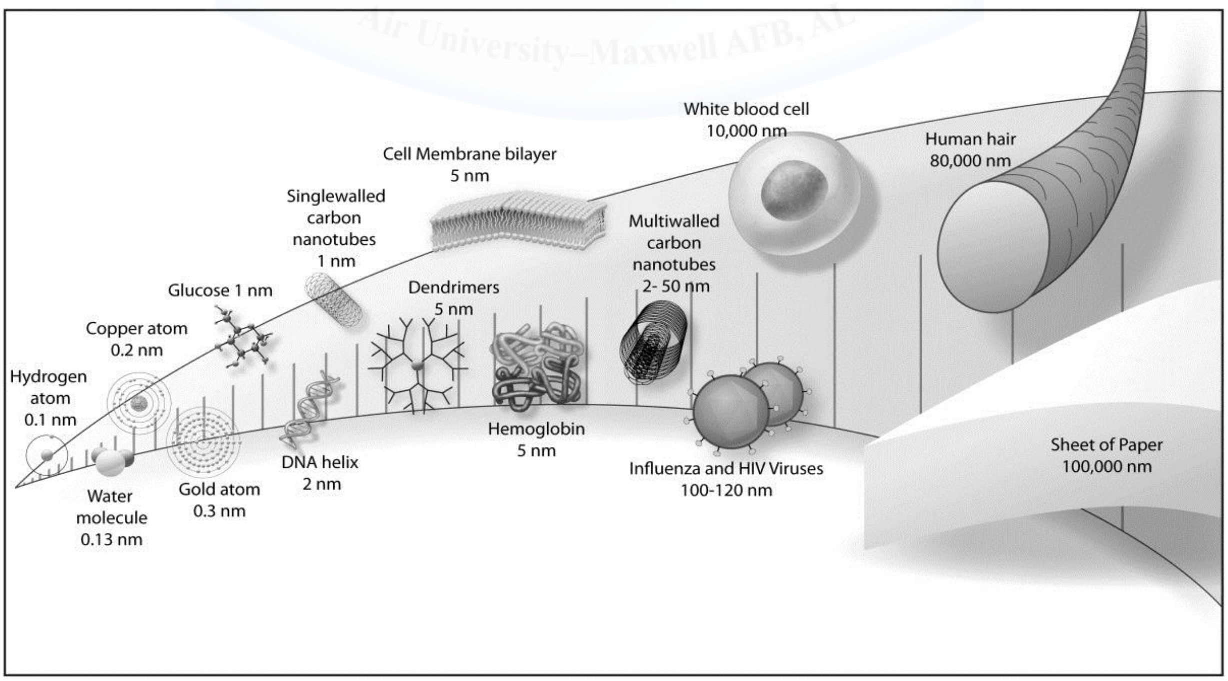

Figure 4. Scale of Nanotechnology.[29]
This figure illustrates the relative size of different items in the Nano-Dimension.

The science and military application of the Nano-Dimension poses tremendous potential to augment, alter, or revolutionize the essence of airpower. The Nano-Dimension is an evolutionary term in meaning and description, but for the purposes of discussing the next domain of warfare, the Nano-Dimension is based on manipulating very small sized matter between 1 to 100 nanometers (or 10^{-9} meter).[30] Over the next decades, scientific forecasters predict nanotechnologies will augment virtually all man-made global products ranging from food, clothing, energy, computing, medicine, and transportation.[31] In the future, manipulating matter in the Nano-Dimension could well become as crucial and ubiquitous to military operations as cyberspace. To borrow from Thomas Kuhn, the broad application of Nano-Dimension manipulation will cause many experts to feel as though they "had been suddenly transported to another planet where familiar objects are seen in a different light and are joined by unfamiliar ones as well."[32] As scientists develop what Eric Drexler (coiner of the term "nanotechnology") calls "atomically precise manufacturing" (APM) within in Nano-Dimension, the potential for creating revolutionary weaponry is simultaneously a significant opportunity and threat for the United States.[33] Like all domains, the United States must dominate the Nano-Dimension to retain military superiority.

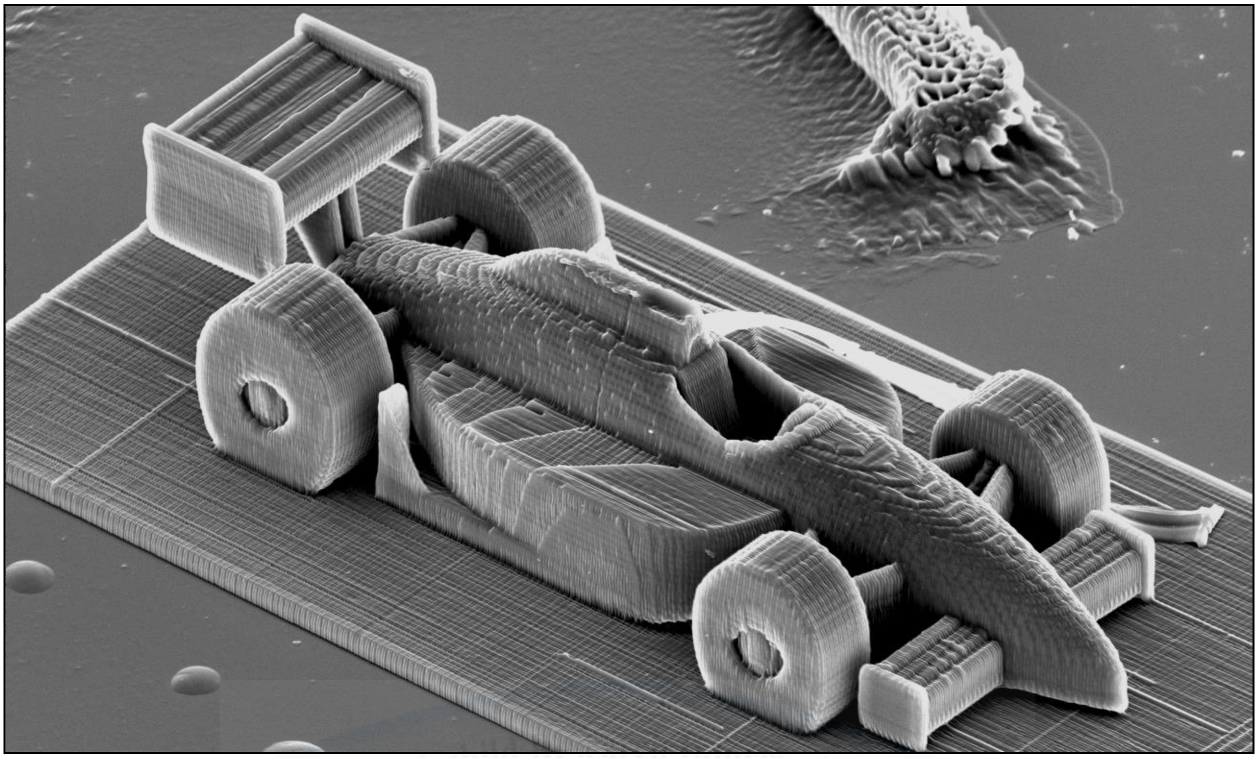

Figure 5. Additive Manufactured Nanoscale Prototype.[34]
This prototype was additively manufactured with a printer capable of precise resolution down to 100 nanometers. This car is approximately 300 nanometers long and 100 nanometers wide.

Developing 4D Printing capability establishes the military infrastructure to exploit and dominate the Nano-Dimension. 4D Printing facilitates domination of the Nano-Dimension by incorporating adaptive designs into nanoscale resolution manufacturing. Dominating the Nano-Dimension will require production ability, and 4D Printing provides the framework to apply nanotechnology to existing materials and weapon systems (e.g., reactive aircraft paint schemes), while also posturing the United States military to harness the potentially revolutionary capabilities enabled through control and domination of the Nano-Dimension.

Postulation 7—Large Scale Non-Additive Defense Manufacturing will become a Liability

> *The global manufacturing industry is gravitating towards additive manufacturing because of the costs savings and complex design capabilities. This trend will continue, and in the coming decades many non-additive manufacturing processes will become economically and technologically archaic.*

With the recent expiration of certain key patents and trademarks, combined with key Printing technology advances, additive manufacturing is poised to begin a significant ramp-up in the global economy over just the next several years.[35] The market-research firm Freedonia Group forecasts over 20% a year growth through 2017 in existing 3D printers as wide-ranging industries including clothing, chocolate, and jet engine fuel nozzles, all seek to capitalize on the cost savings and complex design capability of additive manufacturing.[36] Combining this trend with other technology advances, many non-additive weapons manufacturing projects will become archaic in both cost and capability by the year 2040.

Relying on conventional manufacturing and the traditional warehouse model will elevate the relative costs of the US defense industry (as additive manufacturing promulgates throughout the world), while also stunting much of the technological growth in American weaponry (because of the design limitations of conventional manufacturing). The cost savings and design capability inherent to additive manufacturing will simply relegate many other forms of EDM to niche application. Furthermore, a *lassie-faire* approach to reforming the military-industrial complex will place the United States at a competitive disadvantage, as a military led unity of effort will be required to hasten and vector the transition towards 4D Printing in the defense industry. Rather, to avoid becoming an outmoded liability that is technologically inferior to civilian and international competitors, the US military must strategically shepherd the defense sector's transition towards 4D Printing.

Synthesis

Unlike defense spending to develop directed energy weapons, hypersonics, or stealth, investment into 4D Printing is an investment in process and infrastructure, rather than a product. As envisioned by the preceding Seven Postulations, American airpower in the future will be both circumstantially uncertain and operationally constrained. To retain and expand American military supremacy, senior leaders are faced with the unenviable task of allocating shrinking budgets towards a broader array of emerging technologies in an increasingly dangerous and unpredictable global security environment. Within this context, infrastructure investment is a more appropriate, efficient, and risk-mitigating investment of taxpayer funds than many individual product technologies because it optimally postures the US military for the future, while avoiding over-commitment to single products. Worth clearly listing to aid understanding and evaluation of a new paradigm like 4D Printing, the following list succinctly outlines the potential benefits to the USAF and the US military of 4D Printing investment.

Benefits to the US Military of Investment in 4D Printing

- *Posture to dominate the Nano-Dimension throughout the range of military weaponry*
- *Near-Term improvement in aircraft sustainment through expeditionary 3D Printing*
- *Create diversified weapon systems to protect critical vulnerabilities*
- *Overcome economies of scale to rapidly prototype and field new weapons*
- *Prepare for both high and low intensity combat with scalable manufacturing*
- *Create cost effective small batch airpower solutions*
- *Develop material sciences to create next-generation weapons*
- *Create more effective airpower solutions by programming adaptability into products*
- *Hedge against gradual manufacturing and acquisition obsolescence*
- *Neutralize the strategic benefits of adversary sabotage and design cybertheft*
- *Reap near-term benefits of additive manufacturing while developing next-gen processes*

Recommendations

The purpose of this paper is to persuade the reader of its thesis: to retain American airpower dominance into the year 2040, the United States must lead the world in developing operationalized 4D Printing. This paper's primary purpose is not to outline specific implementation strategies best crafted by select operators and EDM subject matter experts, but rather to catalyze action. However, to augment the primary objective of the paper, the following section discusses five recommendations to Headquarters Air Force (HAF) for creating a path to 4D Printing.

1) Inject Strategic Risk-Taking into the USAF's EDM Philosophy

The current quality control standards for any new USAF project are having the unintended consequence of stifling innovation. Currently, the military-industrial base is effectively restricted from using the latest innovations in the EDM process because of needing to meet the high standard of *only 1 critical failure for every 10 million flight hours*.[37] This well-intentioned standard is crushing innovation because it effectively eliminates strategic risk-taking in aircraft design. Innovation is impossible without calculated risk-taking; the USAF must inject measured risk allowance into the EDM process to capitalize on the revolutionary potential of 4D Printing in the coming years.

2) Recruit Scientists in Nanotechnology, Synthetic Materials, & Additive Manufacturing

Just as the USAF needed organic radar experts to guide the development of radar weaponry, the USAF needs to organically acquire expertise in the fields of nanotechnology, synthetic materials and additive manufacturing to shepherd the implementation of 4D Printing. Currently, the USAF currently retains 2991 active duty scientists and engineers (61XX & 62XX air force specialty codes), and of these 2991, 2505 of them earned their most recent academic degrees in fields relevant to EDM.[38] The USAF should consider a 25% increase in the approximately 2500 EDM personnel. These scientists and engineers should specialize in the 4D Printing related fields of nanotechnology, synthetic materials, and additive manufacturing to form the initial brain trust overseeing 4D Printing development.

3) Implement AFRL's Strategy to Accelerate Operationalizing Additive Manufacturing

Air Force Research Laboratory (AFRL) has devised a sound strategy to accelerate operationalizing additive manufacturing throughout the USAF. Their strategy includes developing updated cost models and risk quantifications for additive manufacturing applications, as well as linking the design process with additive manufactures to create integrated solutions.[39] Increased materials standardization as well as revised structural integrity inspection protocols would also expedite AFRLs ability to implement near-term additive manufacturing solutions for tooling and obsolescent component replacement.[40] AFRL has identified some of the self-imposed challenges obstructing additive manufacturing in the USAF—visionary leadership can overcome many of these challenges.

4) Operationalize 4D Printed Jet Engine Air Inlets

Self-Assembly Labs, a research component of Massachusetts Institute of Technology, has developed a morphing jet engine air inlet prototype with broad potential military application.[41] In the program, partnered between MIT, Airbus, and others, "a single piece of programmable carbon fiber transforms its shape to create aerodynamic advantage and tunable performance. Contrary to traditional mechanical activation, this method requires no complex electronics, sensors, or actuators; it decreases the total weight and minimizes failure-prone mechanisms."[42] The USAF should form a strategic partnership with Self-Assembly Labs or other competing organizations to begin 4D Printing jet engine air inlets within the military.

5) 4D Print a Prototype Micro-Drone

The leitmotif of 4D Printing logically leads to the end goal of eventually 4D Printing completed aircraft—micro-drones are an excellent early phase threshold for this goal. Similar to AFRL's concept for the Low Cost Attritable Aircraft program, the USAF should specifically allocate research funds to simultaneously prove the concept of 4D Printing and produce a tactically useful micro-drone.[43] Developing the process of 4D Printing as well as product of the micro-drone would be goal of this type of program, and it should be rooted in strategic—yet aggressive—risk-taking to catalyze innovation. This type of proof-of-concept would be invaluable towards operationalizing 4D Printing.

Conclusion

4D Printing is both a threat and an opportunity for American Airpower. If harnessed, operationalized 4D Printing could propel American Airpower towards greater sustained superiority. Like any strategy or technology, 4D Printing is not a panacea for achieving American military dominance. However, if the United States ignores or under-develops 4D Printing because of poor investment choices or myopic strategies, adversary offensive and defensive capability could overtake America's asymmetric airpower advantage. Some of the key technological revolutions of the past century have been based on process and infrastructure reform, not specific products. Ford Motor Company revolutionized the automobile industry through the manufacturing process of the assembly line, not a specific car. Google transformed global information by mastering the search engine infrastructure, without creating any data. Apple does not make movies or music, but by creating the digital infrastructure of iTunes, Apple permanently revolutionized the entertainment industry. In the next twenty-five years the world will grow more interconnected, yet increasingly unstable, as globalization and technology progression redefine and render archaic many long-standing military weapons and procedures. To position America's airpower for this unpredictable and changing era, the USAF should focus on acquisition infrastructure reform. Civilian enterprises will push globalization and technology to new levels over the coming decades, but without a military-industrial infrastructure capable of harnessing these forces, America's airpower innovation will stagnate while adversaries exploit the game-changing capabilities of the coming era's technological breakthroughs. This cannot be allowed to happen—the United States must lead the world in national defense 4D Printing.

Notes

(All notes appear in shortened form. For full details, see the appropriate entry in the bibliography.)

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[9] Ibid., 12-14.
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