

# **U.S. NATIONAL STRATEGY FOR ADDITIVE MANUFACTURING**

## **2014 CAPSTONE PROJECT**

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## EXECUTIVE SUMMARY

This report analyzes the national security implications of additive manufacturing (AM), a rapidly evolving disruptive technology, and offers policy recommendations aimed at maximizing its benefits while mitigating any foreseeable threats. It employs a broad definition of national security that includes both traditional, military security and economic security. Though in its nascent stages, AM holds great promises with regard to economic competitiveness, sustainable development, military strength, defense preparedness, and healthcare. Nonetheless, the U.S. must also be cautious of challenges the technology could bring, including competition from foreign states, domestic market disruption, cyberspace vulnerabilities, increased chance of hostile action against the U.S. and its allies, and monitoring difficulties.

The three key findings of this report, which should serve as principles that underpin any policy framework crafted for AM, are that:

1. The U.S. does and will not have exclusive technological leadership in AM, necessitating a move away from unilateral policies to **strategic international cooperation**.
2. AM will have greater game-changing impact on **non-traditional national security** objectives, such as economic competitiveness. It will pose threats to traditional military security as well, but these do not fundamentally differ from the current dangers confronting our security agencies.
3. Despite media hype, consumer AM is unlikely to have significant national security implications in the near future. Key opportunities and challenges in the next five to ten years lie in **industrial AM**, where other states are also focusing investment and R&D.

Informed by these key understandings, the three objectives of AM policy-making should be to (1) reinforce U.S. leadership in AM development and deployment, (2) defend the integrity of our AM capacity, and (3) control the spread of AM to state and non-state actors hostile to the U.S. These objectives shape the report's proposed policy framework, which balances the need to strengthen economic and technological leadership with the prevention of security threats:

- Strengthening technological leadership
  - Promoting innovation & education
  - Enhancing international R&D partnerships
  - Bolstering standards development
- Preventing hostile action
  - Expediting implementation of AM-specific cyber defense strategies
  - Reforming export controls to facilitate permissive licensing and deepen focus on multilateral regimes

Broadly, we emphasize an urgent need for a comprehensive U.S. national strategy on AM. The U.S. is not setting the pace for AM development and risks falling behind not only allies such as European nations and Japan, but also strategic rivals like China. To avoid this, we need greater top-down commitment to establishing the U.S. as a credible player in this fast-emerging market.

## I. INTRODUCTION

Additive manufacturing (AM), a rapidly developing, disruptive technology, will have far-reaching consequences for U.S. national security, here construed to include military power, defensive preparedness, economic competitiveness, sustainable development, and healthcare. Such a broad-based approach is necessary as AM is expected to bring about significant changes across multiple sectors, from military to biotechnology. In addition, global leadership in the 21st century demands a foreign policy shaped by both military and economic considerations. If effectively harnessed, AM could provide a vehicle for mutually beneficial interstate cooperation based on science, technology and innovation (STI), and a venue for the reassertion of U.S. technological leadership.

This issue is of particular relevance to the U.S. government because America does not currently possess exclusive leadership in all aspects of AM technology. Diffusion of leadership in the AM sector significantly degrades U.S. capabilities to monitor the technology's path of development and control its proliferation among hostile entities. This shortcoming is of particular concern because AM is predicted to present both substantial opportunities and threats to U.S. national security, in the realms of both traditional and non-traditional national security, with geopolitical, economic, social, and environmental implications.

To this end, the main questions of this report include:

- What is the future of AM, particularly in the next five to ten years?
- What are the national security threats and opportunities associated with AM?
- How can the U.S. government use policy to maximize benefits and mitigate risks of AM?

Our response to the third question comprises the majority of this report. The main policy objectives are to reinforce U.S. leadership in AM development and deployment, defend the integrity of our AM capacity, and control the spread of AM to hostile state and non-state actors.

## II. BACKGROUND

### **Additive Manufacturing**

AM is a collective term for a group of rapidly developing manufacturing technologies that use the computer-controlled addition of layered materials to create a finished part. AM machines are available in a range of sizes, capabilities, and printing materials, ranging from desktop printers designed for hobbyists to industry-focused resin and plastic prototyping machines and high-end, million-dollar laser sintering machines specialized in producing metal parts.<sup>1</sup>

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<sup>1</sup> Christopher Barnatt. 3D-Printing: The Next Industrial Revolution. Explainingthefuture.com, 2013.

The adoption of AM technology presents new capabilities for manufacturers, with “free complexity” in design, exponential improvements in functionality and efficiency, and the introduction of futuristic technologies such as the bioprinting of cells and body parts. On the other hand, AM also threatens to create disruptive effects in many areas, such as economic security, nuclear proliferation, and geopolitics.

## History

Though AM has only recently begun to enter the public consciousness, the technology has existed for decades, at varying levels of sophistication.

In the earlier stages of AM development, the U.S. held a firm lead role. Domestic firm 3D Systems pioneered the first industrial-grade AM process in 1986: stereolithography (SL), a process that solidifies thin layers of UV-sensitive liquid polymer using a laser beam.<sup>2</sup> Selective Laser Sintering (SLS), now the most commonly used metal AM technology, became available in 1992 with a patent awarded to Stratasys, another American firm. Relatively low-cost, plastic-based 3D printers first came to the market in 1996 with Stratasys’ Genisys machine. Stratasys later acquired MakerBot, producer of a popular consumer desktop 3D printer, as a subsidiary in 2013.<sup>3</sup> Now headquartered in both Minnesota and Israel, Stratasys holds almost 500 AM patents worldwide.<sup>4</sup>

However, as AM matures and companies from around the world enter the market, leadership has diffused over more actors and states. As early as 1988, Japanese and European firms, such as German-based EOS, began to compete in the SL market.<sup>5</sup> In 2008, EOS led the world market in SL and SLS systems.<sup>4</sup> Significant developments have also come from China, Israel and the United Kingdom. In China, R&D has been driven primarily by leading university researchers. In 1998, Peking University began developing technologies similar to fused-deposition modeling, another form of AM.<sup>3</sup> More recently, in 2011, a research team from Huazhong University of Science and Technology created one of the largest SLS machines on the market.<sup>6</sup>

According to the 2014 Wohlers Report, sales of metal AM systems grew 75.8% between 2012 and 2013.<sup>7</sup> Most purchases were made by companies such as Airbus and General Electric (GE), who can use metal AM technology to produce complex parts for next generation aerospace products.<sup>8</sup> On the consumer end, firms such as Shapeways in the U.S. and 3D Hubs in the

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<sup>2</sup> "Patent US4575330." *Google Books*. Web. 10 Dec. 2014.

<sup>3</sup> "About Stratasys." *Stratasys*. Web. 10 Dec. 2014.

<sup>4</sup> "Growth of Metal Additive Manufacturing." *TCT Magazine*. 22 Aug. 2014. Web. 10 Dec. 2014

<sup>5</sup> Wohlers Associates, Inc. *Wohlers Report 2011*. Fort Collins: Wohlers Associates, 2011.

<sup>6</sup> "China Developed the World’s Largest Selective Laser Sintering Equipment." *3ders.org*. Web. 10 Dec. 2014.

<sup>7</sup> Wohlers Associates, Inc. *Wohlers Report 2011*.

<sup>8</sup> "Fit to Print: New Plant Will Assemble World’s First Passenger Jet Engine With 3D Printed Fuel Nozzles, Next-Gen Materials." Last modified June 23, 2014.

Netherlands have attempted to give consumers and individual designers access to more sophisticated levels of AM.

### **State of Technology and Likely Short-Term Developments**

Much of the recent hype surrounding AM has focused on consumer-grade machines. These devices, such as the MakerBot, take advantage of advances in microcontroller technology and recently expired patents to extrude and render models in plastic. Indeed, they are capable of producing models to a reasonable level of precision, and new entrants have dropped the price for entry-level printers from tens of thousands of dollars to around \$1000.<sup>9</sup> However, such printers remain prone to malfunction and can take hours to complete simple projects. Though they have been used to create potentially dangerous objects such as handguns, they remain restricted to printing in plastic, reducing their usefulness. Furthermore, consumers largely lack the knowledge and software to produce their own designs. Thus, although diffusion will likely continue with dropping prices, we do not expect to see significant household printing outside of the hobbyist community in the near future.

Despite receiving less public attention, industrial AM is maturing at a much more rapid pace. In recent years, manufacturers have realized the potential of AM to produce not just prototypes, but functional parts. In the 1980s and 1990s, AM was almost exclusively used as a method of rapid prototyping, casting, and tooling. However, from 2002 to 2012, the proportion of total revenue in the AM industry generated by parts production grew from almost nothing to 28.3%.<sup>10</sup> In particular, industry leaders in the medical, dental, automotive, and aerospace sectors have already integrated AM into critical processes, using it to manufacture highly specialized parts that often incorporate high-performance alloys.<sup>11</sup> For instance, GE Aviation has committed to producing the fuel nozzles for the LEAP engine with metal AM and hopes to produce 40,000 such units by 2018.<sup>12</sup> NASA has also successfully tested AM-printed rocket engine parts able to withstand the heat and pressure required for space launches.<sup>13</sup>

According to researchers at Lawrence Livermore National Laboratory (LLNL), consumer AM is at the “peak of inflated expectations” in Gartner’s Hype Cycle model, characterized by exaggerated predictions of the technology’s potential. Enterprise, industrial-grade AM, however, has moved past the hype trough and is scaling the “slope of enlightenment,” where technology is being integrated effectively into production and best practices are maturing. Although implementation is still somewhat limited by the lack of standards and production quality control,

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<sup>9</sup> “MakerBot Replicator Mini”. *MakerBot*. Published electronically 2014.

<sup>10</sup> Wohlers Associates, Inc. *Wohlers Report 2013*. Fort Collins: Wohlers Associates, 2013.

<sup>11</sup> Royal Academy of Engineering. *Additive Manufacturing: Opportunities and Constraints*. London: Royal Academy of Engineering, 2013.

<sup>12</sup> Wayne King, et al. “Metal AM Today and Tomorrow: HPC and Additive Manufacturing.” PowerPoint Presentation, Lawrence Livermore National Laboratories, Livermore, CA, July 23, 2014.

<sup>13</sup> “NASA Successfully Tests 3D-printed Rocket Engine Parts.” *Deccan Chronicle*, November 14, 2014.

such hurdles are likely to dissipate with continued R&D. LLNL predicts major breakthroughs in the following areas over the next five years, particularly related to the field of industrial AM:

- Increased confidence in part quality through the incorporation of in-situ sensing and feedback control
- Faster build speeds and larger build platforms
- Development of better metal alloys
- Hybridization of materials and multi-material printing
- Embedded electronics

Other areas of growth also show great promise, but are still in early research phases. In the biomedical sphere, for instance, AM production of cells could potentially be used to build replacement organs for transplants. While seemingly the work of science-fiction, such research is presently occurring at Wake Forest University and Yale University, the latter in coordination with the private firm Organovo.<sup>14</sup> These technologies may not be online for decades, but deserve note in terms of the policies that will be required today to ensure and accelerate their progress.

### **III. PROMISES**

From a non-traditional national security standpoint, AM has the potential to optimize business supply chains, enhance product innovation, promote sustainable development, and strengthen economic growth through a revival of the U.S. manufacturing base. In conventional military terms, AM can shorten supply chains, strengthen our defense industrial base and forward operations through the design of new, cheap, and specialized materials, and perhaps someday treat battlefield injuries with regenerative medicine.

#### **Economic Competitiveness**

##### *Shorter Supply Chains*

With AM, products can be made on demand at the point of requirement. Such “just in time” logistics will considerably simplify and perhaps even eliminate assembly lines and supply chains, reducing manufacturing costs as products and parts are re-organized within a single facility.<sup>15</sup> This will be particularly relevant to industries that need to keep an extensive inventory of specialized parts on hand, as they could rely on AM to produce these parts when required.

##### *Product Innovation*

By depositing rather than removing material, AM is able to eliminate many of the restrictions inherent to traditional manufacturing processes. For example, AM enables the production of

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<sup>14</sup> Ziba Kashef. “Yale joins with leader in 3D organ printing to transform transplants.” Web. *Yale News*, New Haven, CT, December 3, 2014.

<sup>15</sup> Michael Ott and Michael Zaeh. “Multi-Material Processing in Additive Manufacturing.” *SFF Symposium 21 Proceedings*, International SFF Symposium, Austin, TX, August 9-11, 2010.

more intricate parts<sup>16</sup> as well as structures difficult or impossible to produce using traditional machine tools.<sup>17</sup> The technology also makes it faster and easier to create prototypes, greatly accelerating innovation and engineering cycles. Further, AM does not require retooling to produce different parts, meaning that individually customized parts can be produced at no additional cost, an advantage known as “free complexity.”<sup>18</sup> Finally, AM makes it possible to create novel materials with customizable properties, such as variable stiffness and conductivity,<sup>19</sup> as well as directly embed multiple materials within a single object during the printing process.<sup>20</sup>

### *Economic Growth*

Analysts predict that AM may have as profound an impact on manufacturing as modern assembly-line factories did in the 20th century.<sup>21</sup> Rapid domestic adoption of AM will create demand for jobs, skilled workers, as well as training and education programs designed to equip workers with AM knowledge, while at the same time reducing the comparative advantage of foreign manufacturers who currently benefit from cheap labor and economies of scale. New markets will be created for goods produced using AM, especially complex and customized products, which will themselves require the growth of new support industries. The expansion and integration of AM into the U.S. manufacturing sector will have significant implications on U.S. macroeconomic figures and strengthen its economic superiority vis-à-vis other nations.

### **Military Superiority**

#### *Efficient Supply Chains*

Just as AM will shorten corporate supply chains, so too will it revolutionize the supply chains of the U.S. military. Instead of maintaining costly strategic stockpiles, our military units will only need sufficient printing capacity and critical raw materials, thus enabling production even in the most austere locations. Furthermore, the military will be able to maintain digital inventories instead of physical ones by storing computer aided design (CAD) files that support production. Consequently, AM technology will result in rapid, targeted, and customized responses as well as reduce supply chain overhead, transportation costs, and other logistical challenges that troops face in the battlefield. Such improvements in the affordability, cycle time, and availability of weapon systems will have a particularly significant impact on aerospace operations.

#### *New Military Technologies*

AM’s ability to produce customized light-weight materials and parts will enable the creation of new military technologies that significantly strengthen U.S. defensive capabilities. Our military

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<sup>16</sup> U.S. Department of Energy, *Additive Manufacturing*, p1.

<sup>17</sup> Timothy Rider. “Picatinny Engineers Look to Printed Metals to Transform Army Logistics, Armaments.” *Picatinny Arsenal*, July 3, 2014.

<sup>18</sup> U.S. Department of Energy. *Additive Manufacturing*, p1.

<sup>19</sup> Ibid.

<sup>20</sup> Michael Ott, and Michael Zaeh. “Multi-Material Processing.”

<sup>21</sup> Sharon Ford. “Additive Manufacturing Technology: Potential Implications for U.S. Manufacturing Competitiveness.” *Journal of International Commerce and Economics*. Published electronically September 2014.

scientists are already designing and constructing items such as printed parts for protective masks, holders for improvised explosive device detectors, medical prosthetics, and explosives. Other avenues of interest include food supplies, medical applications, traditional repairs, and printing of entire component sets that could be assembled to create various equipment.

## **Sustainable Development**

### *Energy Efficiency and Waste Reduction*

AM will demand far less energy expenditure than conventional manufacturing. This is particularly relevant for industries requiring low-volume, high-value parts, such as automotive, aerospace, military and nuclear.<sup>22</sup> For one, AM allows manufacturers to eliminate production steps, reduce raw material wastage, reuse byproducts, and produce lighter, more fuel-efficient components. With the production of parts on demand, the costs of maintaining and transporting stockpiles can also be avoided. Further, AM enables the remanufacturing of end-of-life products to a like-new condition, using only 2-25% of the energy required to make new parts.<sup>23</sup> The DoE's Advanced Manufacturing office has projected up to 50% energy savings for industries where AM is competitively integrated.<sup>24</sup> Taking full advantage of this will enable America to reduce environmental pollution, combat climate change, and—most critically—increase our energy security by reducing dependence on fossil fuel imports from unstable or hostile states.

## **Healthcare**

### *Biomedical Applications*

AM has the potential to create customized prosthetics, implants, replacement tissues and intricate body parts, including blood vessels. Optimal patient care in dentistry, orthopaedics and implantology requires unique and highly customized medical products that identically match the requirements of the patients. Demand exists in the form of one-off components, whose materials and manufacturing standards have to fulfil extremely stringent quality requirements. This also applies to specialized surgical instruments and medical devices. In addition, these products must be made available quickly and cost-effectively. AM is uniquely capable of satisfying these requirements, heralding the dawn of a new type of patient-specific medical care. In this way, test series, prototypes, patient-specific one-off parts and small production runs could be manufactured at a profit. These characteristics will also have implications on the military; for example, advanced battlefield care could be provided remotely, at reduced costs.

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<sup>22</sup> Ken Ma. "Additive Manufacturing Could Reshape the Future." *Innovation* 11, no. 4 (2013, 4th Quarter).

<sup>23</sup> John Sutherland et al. "A Comparison of Manufacturing and Remanufacturing Energy Intensities with Application to Diesel Engine Production." *CIRP Annals: Manufacturing Technology* 57, no. 1 (2008): 5-8.

<sup>24</sup> U.S. Department of Energy, Advanced Manufacturing Office. *Additive Manufacturing: Pursuing the Promise*. DOE/EE-0776. 1. N.p.: August 2012.

## IV. CHALLENGES

### A. Economic Security Challenges

#### Competition from Foreign States

Though not traditionally considered a facet of national security, economic security is likely to become an increasingly salient aspect of the challenges posed by AM technology. Current trends point towards the increasingly widespread adoption of AM methods across industry; for example, a February 2014 survey of 114 companies, constituting a representative cross-section of the manufacturing industry, showed that 66.7% are in the process of adopting AM, while 24.7% plan to do so in the future.<sup>25</sup> In addition, the total worldwide sales of AM-produced parts are doubling every year,<sup>26</sup> and in a 2013 report, McKinsey analysts estimated that AM could have an economic impact of \$230-550 billion a year by 2025.<sup>27</sup>

However, U.S. manufacturers may not be able to fully reap the potential economic benefits of greater worldwide AM adoption because the U.S. is not the sole leader in AM technology, both in terms of capability or market capitalization. For example, of the companies that manufacture professional-grade industrial AM systems, 7 are currently based in China, 6 in Europe, 5 in the U.S. and 2 in Japan. Compared to a decade ago, the focus of the mix has shifted significantly from American and Japanese manufacturers to Chinese ones. In addition, all of the manufacturers of the critical metal powder bed fusion systems are based outside the U.S.: 7 are in Europe and 2 are in China.<sup>28</sup>

Several countries whose scopes rival that of the U.S. have made plans for AM investment. Examples include China, which is establishing 10 “innovation institutes” dedicated to integrating AM into wider industry,<sup>29</sup> and Singapore, which has pledged \$500 million to become the “advanced manufacturing hub of Asia.”<sup>30</sup> In the coming years, centers of AM technology leadership are likely to emerge in Germany, the UK, China, Japan, the Netherlands, South Korea, Singapore, and possibly other countries that have begun investing heavily in the technology, such as South Africa. In addition, many of these countries are investing in attaining a market-leading position in niche AM applications, such as Japan in titanium printing and Germany in printing abnormally long machine parts.<sup>31</sup>

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<sup>25</sup> PricewaterhouseCoopers, LLC. *3D Printing and the New Shape of Industrial Manufacturing*. June 2014.

<sup>26</sup> Wayne King et al. “Metal AM Today and Tomorrow.”

<sup>27</sup> McKinsey Global Institute. *Disruptive Technologies: Advances That Will Transform Life, Business and the Global Economy*. May 2013.

<sup>28</sup> Wohlers Associates, *Wohlers Report 2013*.

<sup>29</sup> Rose Brooke. “China Flexes Muscle in 3D Printing Race to the Top.” *TCT Magazine*, June 27, 2013.

<sup>30</sup> Yi Shyan Lee. “Opening remarks by SMS Lee at the launch of NTU Additive Manufacturing Centre.” Speech, Singapore, May 26, 2014.

<sup>31</sup> Grace, Robert. “China Aims to be Global 3D Printing Leader by 2016.” *Plastics News*, June 26, 2013.

If American investment in the technology does not match that of other states, the U.S. faces a serious possibility of falling behind in the race to develop and adopt AM. This may lead to problems such as larger U.S. trade deficits and reduced ability to influence manufacturing standards and export control agreements. The issue is exacerbated by the fact that much of the R&D for AM currently takes place in the private sector and overseas, which makes it difficult for governmental bodies to monitor ongoing developments.

### **Domestic Market Transition**

Though AM has the potential to create improvements in efficiency across the manufacturing sector, its process of adoption and implementation is likely to have serious disruptive effects if not properly managed. First, the reduction of physical production footprints due to AM adoption may make large amounts of factory space and traditional manufacturing equipment obsolete, raising the question of how best to repurpose, recycle or dispose of this infrastructure. Second, demand for workers with traditional manufacturing skills may fall, leading to structural unemployment and the need for large-scale retraining programs, especially among blue-collar workers in the low-to-medium wage bracket. Third, the supply of workers equipped with AM skills may not be able to keep up with demand, creating a bottleneck on the growth of the AM industry. Fourth, widespread AM adoption may allow many manufacturers to cut out intermediate steps in prototyping, product design, and supply chains, making companies offering such services obsolete. These, and other related transition issues, may discourage manufacturers from embracing AM on a larger scale and realizing the potential benefits in terms of cost, time and energy savings.

### **Intellectual Property Theft**

AM will also complicate intellectual property (IP) protection. Beyond the theft of CAD files, the use of digitizing machines to scan and replicate whole items as single pieces and the use of rapid prototyping to reverse engineer industrial goods also pose challenges. Such IP infringements will be hard to detect, damaging the interests of U.S. businesses and degrading economic competitiveness.

## **B. Traditional Security Challenges**

Much public attention has focused on the possibility of using AM to print homemade firearms and explosives. The open-source gunsmithing firm Defense Distributed has generated particular notoriety for designing and releasing the CAD file for a plastic gun called “The Liberator.” However, we do not believe this to be a source of significant threat. Consumer AM printers that print exclusively in plastic are incapable of creating viable handguns, and the prohibitive cost of industrial metal AM machines—roughly \$1 million for an SLS machine and thousands for titanium powder—makes it unlikely that they will be used to produce items that can be acquired much more cheaply through the black market. Furthermore, modifying border controls to detect such objects requires only a greater outlay of resources to homeland security, rather than

constituting a novel threat. The main focus of our analysis, therefore, will be on complex parts such as nuclear centrifuge or missile components for which industrial AM could provide a less traceable and more cost-efficient means of acquisition and production.

### **Increased Threat of Cyber Incidents**

Since AM involves digital manufacturing processes and databases, the technology will increase our use of cyberspace in a security environment where the scale of cyber attacks continues to increase and nations with competing interests such as Russia are establishing units for cyber offense.<sup>32</sup> As is the case with all digitized information, it will be difficult for the U.S. to trace and contain the espionage of sensitive AM data once files are shared on the Internet. Such heightened vulnerability becomes even more alarming as AM aggravates consequences for data leakage, theft, and corruption. By stealing CAD files for critical parts, hostile state or non-state actors can acquire specialized weaponry and defense systems at far greater speeds. By tampering with CAD files or automated production processes, they can also remotely introduce defective components to critical systems, exposing them to unacceptable levels of risk and compromising operational effectiveness. At present, for example, the DoD supply chain lacks measures to detect and eliminate such low-quality parts, indicating that AM data tampering will likely be difficult to detect without initiatives to improve the current framework.<sup>33</sup>

### **Implications for the Proliferation of Weapons of Mass Destruction (WMD)**

In the past, highly advanced arms and munitions could easily be detected, allowing the U.S. to trace attacks and arms trade to specific state and non-state actors. AM may change this by facilitating the development of WMD programs and complicating efforts to monitor and impede them. The technology makes both information transfer and parts production less detectable and removes production steps involving machining, thereby reducing the level of risk, expertise, and time required for producing key components in missiles and nuclear centrifuges. Nonetheless, threats to WMD counterproliferation efforts are contingent on AM being incorporated into relevant U.S. programs and hence may not be immediate.

### **Implications for Terrorism**

Considering cost-efficiency, terrorist organizations will likely continue to pursue their traditional modes of operation rather than make significant investments to adopt industrial AM. However, it is still possible that terrorist organizations will choose to do so and the U.S. needs to be prepared for the potential consequences. One possible scenario involves AM-facilitated counterfeit trade boosting terrorist financing. According to Interpol, the counterfeit trade for consumer goods is a preferred, low-risk method for terrorist organizations to finance their operations.<sup>34</sup> Especially for

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<sup>32</sup> Office of the Director of National Intelligence. *Statement for the Record: Worldwide Threat Assessment of the US Intelligence Community*. By Senate Select Committee on Intelligence, January 29, 2014.

<sup>33</sup> Senate Armed Services Committee. *Inquiry into Counterfeit Electronic Parts in the Department of Defense Supply Chain, United States Senate, 112th Congress*. S. REP. NO. 112-167.

<sup>34</sup> Laura C. Nastase. "Made in China: How Chinese Counterfeits are Creating a National Security Nightmare for the United States." *Fordham Intellectual Property, Media and Entertainment Law Journal* 19, no. 1 (2008): 153.

short production runs, AM can significantly reduce time and money expended by eliminating the need for molds and complex assembly lines.<sup>35</sup> The impact of this threat, however, may eventually be constrained by countermeasures being developed in the private sector. Another scenario involves terrorist organizations using AM as a less traceable means of acquiring more advanced offensive capabilities, as in the case of AM-facilitated WMD proliferation or receiving state sponsorship. If there exists a state that previously refrained from sponsoring terrorism in fear of international outcry, AM would give it a means of delivering support (e.g., CAD file on weapons) with greater anonymity. Currently, most AM leaders stand against terrorism and designated state sponsors of terrorism are far from developing robust AM capabilities, but the possibilities should not be discounted.

### **Longer-Term Implication for American Leadership**

The U.S. may endure far-reaching consequences if it loses its edge in AM. As explained in section III, the technology holds great promises to improve military strength and economic competitiveness. If it does not maintain leadership in AM, the U.S. risks missing such opportunities while other states exploit them to build better weapons and make their military operations more efficient through superior supply chains. This will put our military at a disadvantage, putting American lives at risk—both those in the U.S. and soldiers fighting abroad against better-prepared adversaries. Moreover, loss of technological dominance will further reduce our monitoring capacity, which has already been compromised due to significant technological advancements and diffusion happening outside the U.S. government. With limited monitoring capacity, the U.S. risks being blindsided to unsuspected developments in AM that could seriously harm our national security.

## **V. POLICY FRAMEWORK**

### **Policy Objectives**

Given that AM presents a vast range of challenges and opportunities, the U.S. needs an effective policy framework that maximizes benefits while minimizing risks. As stated, our key goals should be to (1) reinforce U.S. leadership in AM development and deployment, (2) defend the integrity of our AM capacity, and (3) control the spread of AM to state and non-state actors hostile to the U.S. This section delineates various measures that could be used to meet these objectives over the next five to ten years.

### **Underlying Principles**

#### *Focus on industrial, not consumer AM*

Much has been made of the recent surge in consumer AM devices. However, as discussed earlier in the report, researchers have assessed that consumer 3D printing is still far from technological

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<sup>35</sup> Thomas A. Campbell and William J. Cass. “3-D Printing Will Be a Counterfeiter’s Best Friend.” *Scientific American*, December 5, 2013.

maturity on Gartner's Hype Cycle, low-grade desktop printers are still of limited reliability and usefulness, and access to software for home 3D printing remains limited, as is knowledge of its use. Thus, consumer AM will not be of primary concern to national security in the near future.

Conversely, industrial AM is rapidly maturing, with projected advancements in aspects such as build platforms, materials and feedback controls over the next few years. With SLS capable of printing with high precision and in metals such as titanium, the technology could be used to create a range of sophisticated parts, from centrifuge components to commercial jet engines. Therefore, the proposed policy framework focuses on the opportunities and challenges presented by higher-grade, industrial AM.

### *Focus on economic competitiveness and long-term leadership in STI*

Technological leadership, as a necessary precondition for military strength and national security, can only be achieved through competitive commercial and economic policy. This is especially so in the 21st century, when the line between the defense and commercial sectors is increasingly blurred. Lockheed Martin, for instance, is entering the commercial marketplace in areas such as air traffic management, while Boeing has two Pentagon programs based upon their 737 and 767 jetliners.<sup>36</sup> Further, global leadership today hinges not just upon military dominance, but also aspects of soft power that can only be exercised through economic strength and STI leadership.

Given our lack of exclusive leadership in AM, policy must focus on regaining American technological leadership in the long-term. Focusing more heavily on the prevention of threats was viable in past instances of disruptive technology because the U.S. at least had a quasi-monopoly over capabilities; AM is different and overly cautious security policy targeted at mitigating short-term dangers could risk harming both commercial and military effectiveness in the long-run.

## **A. Strengthening Technological Leadership**

### **A1. Innovation and Education**

In its 2011 Strategy for American Innovation, the Obama Administration laid out broad guidelines for promoting an "innovation economy," including investing in fundamental research, promoting competitive markets and educating a next-generation workforce<sup>37</sup>. Much of this strategy is also applicable to AM. We propose the following ways through which existing policy can be tailored to promote AM specifically.

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<sup>36</sup> Marcus Weisgerber, Vago Muradian, and Aaron Mehta. "Blurred Lines: Commercial, Defense Sectors Begin To Blend." *Defense News*. August 3, 2014. Accessed December 11, 2014.

<sup>37</sup> National Economic Council, Council of Economic Advisers, and Office of Science and Technology Policy. "A Strategy for American Innovation." (2011): n. pag. Whitehouse.gov. The White House. Web. 3 Dec. 2014.

## Increase Investment in R&D

Being a leader in AM technology will benefit the U.S. by boosting domestic industry, creating new jobs, giving an edge in its defense industrial base, and maintaining its reputation as a global leader in advanced technology. R&D is key for retaining that leadership. Crucial centers and drivers of AM R&D will be private firms, universities, and government laboratories. The following policies can help the U.S. government adapt its broad strategies for science and technology to an AM context:

- The White House has already implemented plans to increase grants for advanced manufacturing research.<sup>38</sup> These plans should place greater emphasis on increasing grants for AM. Organizations that may provide such grants include the National Science Foundation (NSF), DARPA, NIST Laboratories, and DoE Office of Science. Grants should continue to encourage collaboration between national laboratories, university researchers, and private industry.<sup>39</sup>
- Agencies should attempt to distribute grants evenly among short-term advances geared at immediate impact, medium-term technologies seeking to establish an industry position, and long-term concepts such as bioprinting with greater uncertainty as well as potential reward. The medium-term category requires particular attention, as it is typically in this phase that AM advances fail to break into practical use.<sup>40</sup>
- Grant-providing organizations should compile agency reports on AM support and circulate them among other relevant agencies such as the Department of Defense (DoD) and the Department of Commerce (DoC).
- Representatives of grant-providing organizations should meet regularly to discuss the advances that have been made through their support, as well as broad strategy for the government investment in AM. Representatives should treat individual grants as part of a collective portfolio and seek balance across all initiatives.
- When working with private industry, the government may adapt existing schemes, such as Research and Experimentation Tax Credit, towards promoting AM research.<sup>41</sup> The IRS should work to change the language of existing codes to specifically include and make relevant exceptions for spending on AM research and industrial applications, and communicate this focus to relevant business sectors.<sup>42</sup>

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<sup>38</sup> Ibid.

<sup>39</sup> "Research Areas." National Science Foundation (NSF) Discoveries. N.p., n.d. Web. 23 Nov. 2014.

<sup>40</sup> Wayne King et al. "Metal AM Today and Tomorrow."

<sup>41</sup> "A Strategy for American Innovation." White House. 2011.

<sup>42</sup> "Audit Techniques Guide: Credit for Increasing Research Activities (i.e. Research Tax Credit) IRC § 41\* - Qualified Research Activities." *Audit Techniques Guide: Credit for Increasing Research Activities (i.e. Research Tax Credit) IRC § 41\* - Qualified Research Activities*. Internal Revenue Service, n.d. Web. 23 Nov. 2014.

## **Support the American Manufacturing Industry**

Boosting U.S. domestic AM capability is of equal importance to maintaining international partnerships in ensuring access to the latest developments in AM. The following policies can help the U.S. government specifically encourage the development of a domestic AM sector:<sup>43</sup>

- Specific programs and incentives should be developed to convert AM technology to enterprise applications. Beyond evaluating ideas in terms of specific market impact, grants could be structured with opportunities (e.g., more grants, loans, venture capital) to help make AM-using enterprises viable in the marketplace.
- Other vehicles, such as venture capital capabilities and the Up America program, should be used to support new ventures in developing and using AM.<sup>44</sup>
- Government agencies should support the domestic AM sector through their own budgets. This is particularly true of the military, which stands to profit greatly from advances in supply chain capability.<sup>45</sup>
- Through programs such as AmericaMakes, the government should continue to link AM to a broader range of industries.
- DoC should lower barriers to entry in AM through its control of the United States Patent Office. By fast-tracking AM-related submissions, DoC can empower firms and inventors with greater confidence to launch projects, seek funding, or license their technology. Such efficiency could also give American firms an edge when competing with international firms in new AM technologies.
- The U.S. patent system should also be improved to effectively address emerging issues with AM design and technology, in order to clarify ambiguities concerning the ownership of designs and strengthen IP protection mechanisms.

## **Educate the Workforce**

The research and implementation of AM will demand a large and qualified workforce at each level of industry. These include academic experts, engineers and designers trained in CAD and AM principles, and technicians capable of installing, operating, and troubleshooting AM machines. Furthermore, interest and knowledge of AM among the general populace must increase if AM is to gain widespread acceptance and use. The following policies can help the U.S. government train a next-generation AM workforce and population<sup>46</sup>:

- DoED should incorporate AM into primary and secondary education through (1) providing entry-level printers such as MakerBots and appropriate software packages to elementary and secondary schools; (2) free AM training for teachers; and (3) curriculum development.<sup>47</sup>

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<sup>43</sup> "A Strategy for American Innovation." White House. 2011.

<sup>44</sup> "About The Startup America Partnership." Startup America Partnership. UP America, n.d. Web. 23 Nov. 2014.

<sup>45</sup> Siavash H. Khajavi, Jouni Partanen, and Jan Holmström. "Additive Manufacturing."

<sup>46</sup> "A Strategy for American Innovation." White House. 2011.

<sup>47</sup> "MakerBot Academy." *MakerBot*. MakerBot, n.d. Web. 23 Nov. 2014.

- DoED should partner with universities and organizations such as the American Society of Mechanical Engineers and the Accreditation Board of Engineering and Technology to formally include AM training in college engineering curricula.
- Financial support should be given for universities to purchase advanced AM machines.
- NSF funding for graduate work should focus on AM to create a new class of AM specialists in both academia and industry.
- DoC should take a leading role in communicating relevant changes in AM policy to both businesses and consumers.

## A2. International R&D Partnerships

While current U.S. innovation strategy is fairly comprehensive and provides a strong foundation for AM technology policy, a crucial weakness is its narrow focus on *domestic* initiatives. Much development in AM will be driven by private sector leaders beyond U.S. borders. Robust AM initiatives are emerging in Europe and Asia, establishing various countries as leaders in niche areas.<sup>48</sup> One important sector that presently lies outside U.S. capability is the production of professional-grade industrial AM systems, especially metal powder bed fusion systems, which is dominated by Europe. As networks such as the European Union intensify international collaboration, it is increasingly likely that crucial breakthroughs in AM will be achieved through partnerships rather than a single agency.

Hence, it is necessary that the U.S. put in place networks for foreign collaboration in AM, as well as tap into existing networks. These partnerships should include both public and private organizations. This will allow the U.S. to benefit from expertise developed in any of the multiple R&D hubs worldwide.

Given the many strategic realities that bear upon government-to-government partnerships and limit open dialogue, the most productive international R&D efforts are likely to be driven by the private sector. Businesses at the forefront of AM technology are often multinational in scope, and many have already built sophisticated linkages across borders. 3D Systems, for instance, has facilities and employees in 25 locations globally, and Stratasys has been 45% foreign-owned since its merger with leading Israeli systems manufacturer Objet. Policy should thus focus on supporting Track II diplomatic efforts, encouraging American scientists, academics and firms to collaborate across borders.

To ensure that these collaborations are effective, we need to know *who* to work with, and adopt carefully calibrated strategic postures towards different categories of foreign partners. Our approach should be as follows:

- First, the U.S. should collaborate actively with Europe, which remains our core strategic ally on issues of global security. Germany, the Netherlands, and the UK in particular

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<sup>48</sup> Wayne King et al. “Metal AM Today and Tomorrow.”

have established themselves as leaders in industrial AM, and are likely to maintain this leadership over the next five to ten years.

- Second, the U.S. should also tap into the niche capabilities of smaller R&D hubs such as Singapore, Japan, South Korea, and (to a lesser extent) South Africa. Although not as advanced as Europe in AM, these countries are intensively pursuing AM research and have made breakthroughs in specialized areas. They are also reliable allies that the U.S. can cooperate with on a broad range of issues.
- Third, the U.S. should seek active, albeit limited partnerships with China and Israel. China has developed an edge in metal AM,<sup>49</sup> and deepening economic interdependence between our nations has laid strong groundwork for healthy collaboration. However, China remains a formidable strategic rival, and we should still be wary of sharing any sensitive technologies with military implications. Israel is a significant producer of industrial AM systems, but in view of its relatively aggressive intelligence posture towards the U.S, we should adopt a similarly cautious approach.
- Finally, while Russia continues to lag comparatively in its AM capabilities, the U.S. should keep a close watch on any forays it makes into AM, and forge partnerships similar to those with China should the need arise.

### **A3. Standards Development**

The lack of standards for quality control of AM-made parts has been a key barrier to widespread technology adoption. Standards need to be created on multiple fronts, including design, test methods, material characterization, production process, software compatibility, and data processing. To maximize benefits from the technology, the U.S. needs to assume leadership in standards development.

First, the U.S. should expand investment in domestic standardization initiatives. With the DoE's national labs operating 32 of the 500 fastest supercomputers in the world, the U.S. is well-positioned to develop standards, using computer modeling and simulation alongside real-time monitoring and control software.<sup>50</sup> The government should increase funding and support for domestic programs such as LLNL's Accelerated Certification of Additively Manufactured Metals and NIST's Measurement Science for Additive Manufacturing Program.

The U.S. should also increase global collaboration in order to ensure that standards are developed and promulgated based on an accurate understanding of the state of AM around the world. Building partnerships with existing standardization initiatives, such as the EU Support Action for Standardisation in Additive Manufacturing (SASAM), can help ensure this. In

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<sup>49</sup> "Chinese Scientists Develop Liquid Phase 3-D Printing Method Using Low Melting Metal Alloy Ink." *Metal Additive Manufacturing*, October 5, 2014. Accessed November 7, 2014.

<sup>50</sup> Ben Dotson. "Supercomputers: Extreme Computing at the National Labs." *U.S. Department of Energy*. Last modified September 4, 2013.

addition, some U.S. entities are already involved in organizations that are active in developing AM standards. For example, the American National Standards Institute, a private non-profit organization, is part of ISO's technical committee on AM (ISO/TC 261), and NIST is a member of ASTM's committee on AM technologies (ASTM F42). The U.S. can use the expertise gained through its domestic initiatives to increase its influence within these frameworks.

Finally, the U.S. should design programs to promote standards adoption and implementation domestically. Such programs could be propagated via existing public-private channels such as AmericaMakes and the U.S. Small Business Administration. One example would be to hold workshops for the private sector regarding the potential impacts of AM standards on business practices such as insurance, especially in relation to product liability and recall claims.<sup>51</sup> For instance, clarifying where accountabilities lie for defects accrued in the production process will significantly aid confidence in and further adoption of AM technology.

## **B. Preventing Hostile Action**

Although we should aim to maximize AM's commercial and economic potential, AM's growth also poses risks of hostile action that we cannot ignore. Thus, as the U.S. strives to strengthen our long-term technological leadership, we need to adopt appropriate measures to mitigate short-term security threats. Through (1) cyber defense and (2) export controls, we aim to ensure the integrity of our AM sector and prevent the proliferation of lethal capabilities to dangerous actors.

### **B1. Cyber Defense**

The U.S. should match adoption of AM technologies with rapid advancement of cyber defense capabilities in both the public and private sectors. Indeed, the U.S. has already developed an extensive cybersecurity strategy that could meet a wide range of risk mitigation needs sparked by AM. However, AM amplifies the deleterious consequences of cyber-attacks—the theft of a CAD file for U.S. weapon systems, for instance, becomes functionally equivalent to theft of the physical product itself—and such unprecedented entanglement of the virtual and physical necessitates that cyber policy is informed by an understanding of its deeper, farther-reaching implications in a new AM reality. Broadly, the U.S. needs to expedite implementation of proposed initiatives and prioritize AM-specific cybersecurity program development in preparation for the upcoming mainstream adoption of AM.

The 2011 International Strategy for Cyberspace and the 2013 Executive Order for Improving Critical Infrastructure Cybersecurity laid out a sweeping strategy for enhancing the security, reliability, and resilience of networks through international cooperation and cybercrime law enforcement. This action plan has been followed by targeted initiatives from various government

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<sup>51</sup> Ingrid Hobb. "Additive Manufacturing - Insurance Risks." Youtube video. 7:53. July 14, 2014.

agencies that, upon successful implementation, may generate effective risk mitigation strategies for AM such as: (a) better safeguards in AM CAD files, software, and hardware<sup>52</sup>; (b) a secure and functional database structure for AM that enables access and use by various authorized actors<sup>53</sup>; (c) timely detection and incident response for cyber-attacks targeting AM systems<sup>54</sup>; and (d) a stronger capacity in the global private sector to reduce the risks of AM-facilitated IP infringement.<sup>55</sup> Application of such strategies, however, has been slow and the potential has yet to be realized. For instance, government agencies still lack appropriate incident response plans even though a comprehensive framework was released in 2012.<sup>56</sup> U.S. capacity to mitigate AM risks will depend on the timely and effective implementation of our strategies, which should aim to match or exceed the pace at which the public and private sector are adopting AM.

In addition to the general increase in funding for cyber security initiatives, the U.S. should also prioritize the development and execution of programs designed to address AM-specific needs.

### **Prioritize R&D for AM-specific Cyber Incident Response Plans**

AM data theft and corruption are especially time-sensitive. Without timely detection and mitigation, compromised parts could enter into critical systems and stolen files could reach actors with malicious intent. To meet the threat effectively, the U.S. should prioritize the development of tools to detect, contain, and recover tampering in real-time and devise response plans for eradicating or disabling sensitive data that have been stolen or leaked to the wider Internet. Options in addition to federal R&D would include supporting private sector initiatives, such as Quantum Material Corp's anti-counterfeit nanoscale market technology,<sup>57</sup> and convening government-sponsored competitions modeling the DARPA Cyber Grand Challenge, where experts compete in reverse engineering software to find flaws and create improved replacements.

### **Develop a Secure, Resilient, and Accessible AM Database**

In 2012, the DoD developed a plan for an enterprise cloud environment that secures and delivers information more efficiently. The current strategy incorporates various risk mitigation methods, including the use of different network infrastructures and higher level security domains for sensitive data exchange. The White House Office of Science and Technology Policy and the OSD have initiated dialogue on the creation of an AM database. Continued discussion ensues for the creation of a concrete action plan, grounded in careful consideration of how such database management strategies and other elements such as information classification structures would apply for AM systems.

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<sup>52</sup> Department of Defense and General Services Administration. *Improving Cybersecurity and Resilience through Acquisition*. Washington, D.C.: November 2013.

<sup>53</sup> Department of Defense. *Cloud Computing Strategy*, by Teresa Takai, et al. Washington, D.C.: July 2012.

<sup>54</sup> Department of Commerce. *Computer Security Incident Handling Guide: Recommendations of the National Institute of Standards and Technology*, by Paul Cichonski et al. Washington, D.C.: August 2012.

<sup>55</sup> Ibid.

<sup>56</sup> United States Government Accountability Service. *Agencies Need to Improve Cyber Incident Response Practices*. Report to Congressional Requesters. April 2014.

<sup>57</sup> Phil Taylor. "Anti-Counterfeit Tech Developed for 3D-Printed Objects." *Securing Industry*, July 1, 2014.

## **B2. Export Control**

The U.S. already has unilateral and multilateral export controls for a comprehensive range of munitions and dual-use technologies. AM is unlikely to produce security threats that fall far outside the coverage of these existing frameworks and there is thus no pressing need for a standalone regime for AM. The central question is instead how our current approach must be adapted to a new reality where AM is prevalent in both commercial and military spheres. The key challenge is how to avoid compromising objectives of economic competitiveness beyond what is absolutely necessary to prevent grave threats to national security.

### **Key Principles**

Two key principles should inform the U.S.' approach to regulating AM:

*First, the U.S. should take a more relaxed and permissive approach to export licensing, and only add elements of AM technology onto control lists - whether unilateral or multilateral - if a stringent set of criteria is met.*

The following general criteria should bind any restrictions placed upon unclassified AM technology:

- There is no foreign availability outside participating states, and other actors are unlikely to develop the technology for a significant period of time
- Effective control over the export of the technology is possible
- Clear and objective specification of controlled items is possible
- The restrictions do not impose economic losses and inefficiencies disproportionate to their potential security benefits<sup>58</sup>

The first three criteria already govern the selection of items for control under existing frameworks. We should recognize, however, that the former two will prove particularly challenging to assess in the context of AM; the rapid diffusion of capabilities across both public and private spheres makes it harder to ascertain foreign availability and renders effective control—especially of virtual items such as software and data files—more challenging.

The last criterion is not currently emphasized in export control regimes, but should be added to ensure that we fully exploit the economic opportunities offered by AM. Specific questions that must be asked include: (1) Will the restriction invite retaliatory controls from any AM leader whose expertise and technology the U.S. needs to tap on? (2) Do other exporters have more lenient licensing regimes for the item? (3) How will that harm the competitiveness of American producers on the global market? Indeed, these considerations should govern the regulation of all technologies and inform our licensing processes for conventional manufacturing as well.

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<sup>58</sup> National Research Council. *Beyond "Fortress America" National Security Controls on Science and Technology in a Globalized World*. Washington, D.C.: National Academies Press, 2009.

Two further changes should be made in line with the adoption of more permissive licensing.

- First, while some regimes default to denying an export license if the deadline for a decision is reached without a clear conclusion, this approach should be abandoned in favor of granting the license as the default option, except for specific products or components deemed to be very sensitive.
- Second, the U.S. should strengthen mechanisms for the regular review and, if necessary, removal of controls. Indeed, multilateral regimes such as Wassenaar and the Nuclear Suppliers Group (NSG) have established technical experts groups (EGs) to ensure that control lists are complete and up-to-date. However, these EGs still focus on adding new items to the lists, and should do more to reexamine existing controls. Perhaps, as recommended by the National Research Council in *Beyond Fortress America*, “sunset requirements” should be applied to all controlled items, requiring regular findings to be made that removing them from lists would pose a severe threat to U.S. national security.<sup>59</sup>

Negotiating a careful balance between economic and security impetuses will be very challenging and more permissive export licensing may cause harm should careless decisions be made. We must therefore ensure a balanced and informed decision-making process, involving defense and commercial experts from both public and private spheres.

*Second, the U.S. should reduce its traditional reliance on unilateral control lists, and shift towards the strengthening of multilateral regimes.*

Unilateral export controls will continue to be important, but only for highly classified niche AM capabilities developed exclusively within the U.S. Given the relatively decentralized development of the technology and our lack of exclusive leadership however, breakthroughs are more likely to originate from unclassified private sector R&D in various countries, thus raising the importance of international, cross-sector frameworks. The U.S. is already party to numerous multilateral control regimes, such as the Wassenaar Arrangement, the Nuclear Suppliers Group, the Australia Group, and the Missile Technology Control Regime. Of these, Wassenaar should be the most relevant and effective for regulating AM. It covers a broad range of dual-use technologies. Moreover, almost all current global leaders in AM technology—Germany, the Netherlands, the UK, Japan, South Korea, and South Africa, for instance—are already participating states. Nevertheless, we should adapt and utilize all relevant frameworks.

The following improvements should be made to existing export control regimes:

- Language must be updated to cover not just subtractive, but also additive technologies. For instance, Article 2.B.1. (Materials Processing) of Wassenaar controls “machine tools for removing (or cutting) metals, ceramics or “composites” [...]” Such specific references to machines that “remove” or “cut” material must be generalized.

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<sup>59</sup> Ibid.

- Keener focus must be placed on restricting software and data transfer. Most categories in Wassenaar, for instance, still emphasize hardware controls, with relatively minor sub-sections on software. Even regulations for “information security” (Category 5 Part 2) are still targeted primarily at physical information and communications technology systems.
- Some actors at the forefront of AM innovation are not presently members of these regimes, so an active effort should be made to bring them on board where appropriate. Smaller states that are emerging as strong players on the global AM market and can be expected to align with the U.S. (e.g. Singapore) should be a particular target.

With greater reliance on multilateral export control arrangements, the U.S. will need to craft a careful diplomatic approach for amending the lists whenever necessary. This will broadly resemble the strategy laid out earlier in the report for international R&D partnerships.

Given that Germany, the UK, and the Netherlands are very much at the forefront of AM development, our traditional approach of leveraging these transatlantic partners will continue to be effective. However, significant breakthroughs are also taking place in smaller R&D hubs such as Japan, South Korea, and South Africa, and we should seek to secure their cooperation as well. Particularly when the failure to achieve regime-wide consensus necessitates informal negotiations with a smaller subset of countries, we must ensure that these emerging centers of influence are not left out. Furthermore, while Russia is not expected to emerge as a global leader in AM given current trends, its strategic heft, aggressive foreign policy and disquieting relationship with destabilizing actors on the global stage—particularly Iran—necessitates that we closely monitor its export activity and leverage specific mutual interests to prevent it from blocking consensus.

As many emerging AM leaders are not members of these multilateral control regimes, we will need to expand outreach efforts beyond these frameworks as well. China and Israel have already broadly aligned their export controls with Wassenaar standards, but we need to enhance bilateral engagement to ensure this continues as AM is integrated into Wassenaar. Smaller R&D hubs like Singapore are also not party to any international control regimes—primarily because their economies are overwhelmingly export-driven—and the U.S. should therefore monitor and influence their export of any niche AM capabilities through appropriate diplomatic channels.

### **Specific Targets for Control**

Five particular elements of the AM process that should be controlled are: (1) materials, (2) hardware, (3) CAD files, (4) software, and (5) tacit knowledge. Once the four general criteria laid out earlier in the section are satisfied, the following criteria should govern decision-making on what items in each specific category should be considered for control:

- *Hardware*: If an AM printer can achieve a degree of precision equal to or greater than that of subtractive machine tools currently being controlled, the machine or its critical components should be considered for control.
- *Materials*:
  - (1) If AM printers enable the production of already controlled parts using different materials than those used in subtractive methods, the specific grades of those materials refined enough for AM production should be considered for control;
  - (2) If AM technologies enable the design of new materials with unprecedentedly enhanced properties (e.g., durability, elasticity) and these can be used to produce parts of equal or higher fidelity than what is presently possible, they should also be considered.
- *CAD files*: If a CAD file can be used to produce an already-controlled critical part, it should be considered for control. An understanding needs to be established that the transfer of CAD files for a particular component is functionally equivalent to the export of the final part itself.
- *Software*: Any software specifically associated with controlled AM hardware should be considered for control.
- *Tacit Knowledge*: Any knowledge/expertise critical to the operation of any other element controlled—whether hardware, materials, software, or CAD files—and impossible to acquire from open sources outside participating states should be considered for control.

Realistically, the latter three elements will prove difficult to control in this global and digital age. The chaos caused by cyber criminals such as Edward Snowden has proven that our systems remain very vulnerable to damaging leaks. Thus, as we fight to strengthen our cybersecurity, effective regulation of the first two elements—materials and hardware—will remain critical. In particular, materials are a strategic target for controls; high-performance industrial AM relies on far more refined materials than conventional manufacturing, thus boosting the effectiveness of careful export control as a means of hampering production.

## VI. CONCLUSION

AM is still an evolving technology and may not fully take hold of global production processes in the immediate future. However, for policy to keep comfortable pace with technology, there is an urgent need for the U.S. national security apparatus to step back from its short-term priorities, trace AM's likely path of development, and devise prudent strategy for the U.S. to navigate this path going forward.

This sense of urgency is motivated partly of course by the pace of the technology's evolution. As this report has outlined, industrial AM in particular is rapidly maturing and will see significant

breakthroughs in the next two to five years, potentially even replacing conventional manufacturing completely for short production runs or areas where mass-customization holds high value.<sup>60</sup> More critically, however, we should be driven to action by the realization that the U.S. is not setting the pace for AM innovation and risks losing control of a technology that is embedding itself firmly in both our military and commercial sectors.

China is pouring considerable investment into AM—driven particularly by the threat it poses to their current dominance of the global manufacturing base—and falling too far behind our foremost strategic rival will have implications for both American military and soft power. We may not be too concerned about our allies in Europe and their present dominance over systems production, but having to import all our AM machines will still be less than ideal. America needs to strive for leadership, and the very fact that a country as small as Singapore has invested in AM on a scale that dwarfs the \$30 million in federal funding committed by President Obama in 2012 is a sure sign that we have not done enough.

Indeed, the U.S. has started paying some attention to this emerging technology, and the establishment of NAMII was an encouraging step forward. Yet, AmericaMakes' focus on applied design and engineering around levels 7 to 9 of the technological readiness level (TRL) scale is ultimately inadequate—and perhaps somewhat premature—given our relative weakness in both the basic research at TRLs 1 to 3, and the development, demonstration and commercialization from TRLs 4 to 7. The U.S. should not be content with finding innovative uses for 3D printers developed in Europe or new powdered metal alloys invented in China. Although seeking exclusive leadership is an unnecessary and far too competitive a strategic posture in today's world, we should still strive to be among the global leaders in such core capabilities and support the private and federal researchers who can make it happen.

Further, our current reliance on bottom-up initiatives to drive AM innovation is inadequate. Governments in Germany, China, Singapore, and especially the UK have all articulated broad national strategies and such top-down commitment to developing the technology is a necessary signal to both domestic and foreign actors that the U.S. remains a serious and credible player in this fast-growing market. The framework proposed in this report offers a broad overview of what such a national strategy could include, what key principles should underpin it, and what it should seek to accomplish. Its relative focus on non-traditional security objectives such as economic competitiveness sets the framework apart from our conventional approach to technology policy, but AM is after all an unconventional technology that demands a novel mindset from those grappling with its implications that are yet to be fully comprehended.

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<sup>60</sup> National Intelligence Council, *Global Trends 2030: Alternative Worlds*, December 2012, pp. 90.