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Securing Digital Supply Chains for Manufacturing, Maintenance, and Sustainment:

Scaling the Commercial and Defense Industrial Base through Secure Digital Distributed Additive Manufacturing

ABSTRACT

The development of additive manufacturing technology and production systems has the potential to reshape global manufacturing competitiveness, reinforce the defense industry, and reshore jobs to the United States, and do so in a way that enables high quality job growth in both urban and rural areas [1][2][3]. This is largely due to the potential for creating digitally secure supply chain networks of flexible additive manufacturing factories managed and operated by a trained or retrained skilled workforce that can manufacture components at scale when and where they are needed for defense, industrial, and consumer use [4].

This vision, however, is currently hampered by the relatively high cost of additive compared to conventional manufacturing methods at scale. In the critical area of metal additive, this is driven by yields that typically remain lower than conventional manufacturing techniques, which means that further in-situ process monitoring and real-time build controls need to be implemented. Critical properties such as surface roughness and materials properties, as well as a lack of capability for building larger structures all limit the metal components that can be additively manufactured today. Digital thread connectivity and interoperability is lacking, slowing the speed of developing these factories, reducing productivity, throughput, and return on investment. Further, today it often cannot be ensured that critical information, such as design and build instruction files, remain secure and trusted during design, in transit, and while on the machine, hampering the building of a national network of additive factories across the defense industrial base. Solving these challenges will result in a more ubiquitous use of additive technologies for rapid maintenance and sustainment as well as enable technical overmatch for the Department of Defense.

The key to solving these challenges is to bring together multi-disciplinary teams, including mechanical, electrical, materials, optical, controls, and software engineers, in partnership with leading national laboratories, government agencies, and commercial entities. Building and supporting a distributed network of digital and additive factories will result in greater national security and more effective crisis management by enabling a rapid and flexible response to global supply chain disruptions. This paper specifies what is needed to build a secure, flexible, and distributed manufacturing capability in the United States. It details how the following technologies need to be developed: a) a digitally-connected raw materials supply chain; b) integrated digital design, simulation, and quality assurance tools; c) reliable and secure additive manufacturing machine hardware built to specified standards; d) multi-factory planning and balancing software; and e) a cybersecure digital supply chain network linking each of these critical components in a way that ensures build instructions are not tampered with and that inherent intellectual property of design and manufacturing know-how is not compromised (Figure 1) [5][6].

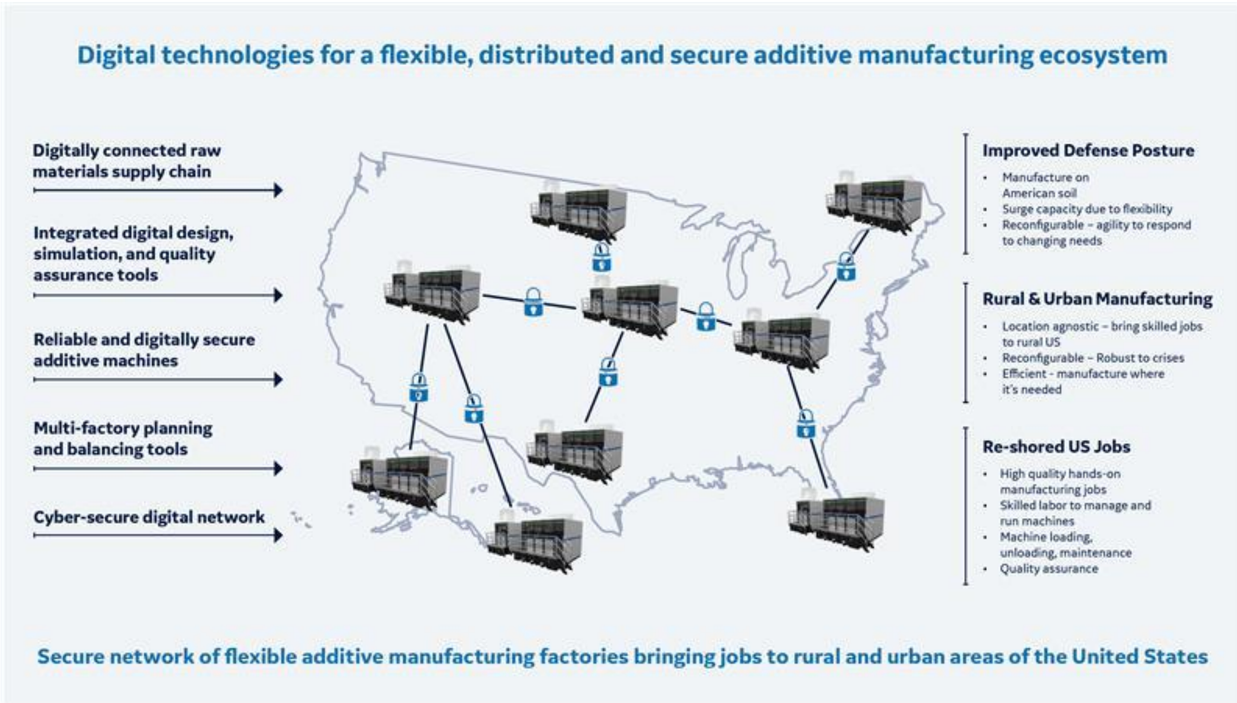

Figure 1. Digital technologies enabling a secure, flexible, and distributed additive manufacturing ecosystem for the United States

INTRODUCTION

In its most developed and robust form, additive manufacturing enables the conversion of digital designs into physical components. As such, additive machines are extraordinarily versatile. They are flexible in what they produce; can be in geographically distributed factories; and can provide supply chain robustness by creating a network of manufacturing options. The United States can use the flexibility of additive manufacturing technology to diversify its manufacturing base both in terms of what is manufactured and where the manufacturing is performed. A networked system of geographically distributed factories with additive machines will provide a domestic supply chain that can be instantaneously reconfigurable to address sudden crises, like the COVID-19 pandemic that has necessitated the sudden mass production of, e.g., ventilators and personal protective equipment [5]. Due to the flexibility of additive manufacturing, distributed factories could be placed in both urban as well as rural areas, providing high quality skilled manufacturing jobs across the United States. In addition, the placement of factories closer to the product point-of-need would save transportation costs and simplify logistics. Further, when effectively deployed and supported, additive manufacturing can be highly mobile and enable forward manufacturing for maintenance and sustainment of defense and industrial assets at or near the point of use.

The jobs created by this distributed additive factory model for the U.S. will be high-quality manufacturing jobs that can be much more protected against overseas outsourcing to lower-cost locations as compared to traditional low-skill labor-intensive manufacturing methods. Each factory would require skilled labor to manage and run the additive machines. Skilled manufacturing trades will be needed, including the loading of raw material powders into machines, the removing of residual powder after builds are complete, the maintenance of the high-tech hardware and software, final post-build processing of the part, including the heat treatment in a furnace, removal from the build plate, and final machining and quality assurance. High-quality jobs will also be created in supporting technical and engineering functions, such as computer-aided design, simulation, print file development and testing, logistics, and materials sourcing.

State-of-the-art metal additive is able to build many critical components and product structures today. However, the vision outlined above is currently hampered by the relatively high cost of metal additive compared to conventional manufacturing methods. This is driven by yields that typically remain lower than conventional manufacturing techniques, which means that further *in-situ* process monitoring and real-time build controls need to be implemented. Critical properties such as surface roughness and materials properties, as well as a lack of capability of building structures larger than $0.1m^3$, all limit the metal components that can be additively built today. Digital thread connectivity and interoperability is lacking, slowing the speed of developing these factories, reducing their productivity, throughput, and return on investment. Furthermore, today it often cannot be ensured that critical information, such as design and build instruction files remain secure and trusted during design, in transit, and while on the machine, which hampers the building of a trusted, secure and competitive national network of additive factories across the defense industrial base. Solving these challenges will result in a more ubiquitous use of additive technologies for rapid sustainment as well as enable technical overmatch for the Department of Defense [7]. The solution will require the integration of multi-disciplinary teams, including mechanical, electrical, materials, optical, controls, and software engineers, and will require partnerships across leading national laboratories, government agencies, and commercial entities.

To build this additively-enabled distributed network of factories, research and development is needed in several key areas. First, an evolved class of additive machines will be required. These machines will need software and controls solutions that are designed to be robust and can recognize and successfully adapt to a diverse set of build instructions that will be required by flexible factories. Second, next-generation design-to-build software tools and models will be required to accurately predict the final outcomes of the additive build process. Such tools will allow component designers that are remote from the factory to be confident that the additive machines will build components to their design intent. The development of standards for the materials, machines, and processes used and the ability to remotely evaluate how individual additive machines are performing with respect to those standards are needed to enable a flexible manufacturing chain [8]. The compilation and dissemination of such standards will require a knowledge base and artificial intelligence software capable of tracking the materials and process capabilities for each of the additive machines. Lastly, a comprehensive set of software and algorithms will be needed to manage the remote factories [3], including optimization of factory load balance and inventories of raw materials, management of personnel resources, and sourcing of capital equipment and maintenance services.

Importantly, this software will need to be linked in a digital network that is secure, so as to enable the trusted transmission of design files to the factory machines. Such a network will also require that files remain unmodified both in transit and while on the machine during the build. The files will need to be verified anytime anyone in the chain wishes to validate component integrity and pedigree, protect against tampering with component quality, or protect against the loss of intellectual property. Factory planning, factory status, and product demand are other types of proprietary information that will also need to be protected. For defense-related manufacturing, industrial-ready commercial systems need to be developed for a scaled and secured national defense network for additive manufacturing. This system will enable secure control of additive parts manufacturing from design through production by securing and orchestrating the additive digital thread, including the control targets (e.g., the additive machines and their control systems), design simulations and engineering models, and machine parameters (e.g. technical data packages). These systems will need to enable interoperability with existing defense industry capabilities, including data repositories, design tools, additive machines, and post-processing methods. These digital additive systems will enable the scaling of a national flexible ecosystem for additive machines with securely-delivered content from technical designers to manufacturers in the defense industrial base in order to drive innovation, productivity, security, return on investment, and technical overmatch.

SECURE, FLEXIBLE, AND DISTRIBUTED MANUFACTURING

Distributed manufacturing is a means of decentralizing manufacturing capability from a small number of legacy industrial regions to a plurality of strategically chosen locations, which are connected and controlled across the Internet to prioritize and dispatch work orders, share build files and post-processing instructions, and enable digital modeling and analytics collaboration. Legacy factories often represent substantial sunk-cost and high barriers to entry, including co-dependence on geography-based ecosystems such as access to specialized talent, support industries, and transportation and ports. In contrast, distributed additive manufacturing enables a manufacturing footprint to be rapidly established in a chosen locale – with less upfront cost to break ground – with additional value being provided through advanced software and analytics – either onsite or remotely. Positive outcomes include the ability to: manufacture closer to the point of highest need and/or lowest cost, manufacture at the location of available manufacturing talent, and have resilient/ redundant networks of manufacturing sites. This inter-connectivity of manufacturing sites enables the manufacturing ecosystem to be mobilized as a system-of-systems to resiliently respond to a range of demand and supply scenarios – from complete focus on locally demanded parts (e.g., repair parts) all the way up to sudden bursts of national need (e.g. multiple sites building the same parts).

By placing the points of manufacture closest to the points of need, obvious simplifications can be made in the way raw materials are stocked, the manner in which goods are transported to their points of sale, and the way inventory is managed at a local level. Importantly, an additively-enabled distributed manufacturing network additionally provides an unrivaled agility for modulating production – that is, adjusting the production of goods almost synchronously with the ebbs and flows of local market demand – while also allowing for near-instantaneous changes in production mix. In additive production, within a single site or across sites, large volumes of parts could be produced utilizing the entire machine fleet, or high-mix production could be attained by sending various parts to different printers concurrently. Moreover, various parts can even be printed on the same build plate, thereby increasing both the throughput of the production site and the overall mix of production. In this way, distributed additive manufacturing sites could easily be tailored to both national and defense manufacturing needs, as well as local or regional needs – or a dynamic between both based on market conditions.

Distributed additive manufacturing will allow for the shrinkage of the supply chain, a reduction in stored parts and finished goods inventory, a reduced dependence on imported goods and raw materials (including through the efficient reuse of scrap powder for additive printing), and an increase in the speed of delivery of goods.

Distributed additive manufacturing will provide the United States with a critical capacity for responding to national and local emergencies and crises. Take, for instance, our nation’s early response to the COVID-19 pandemic and the crippling need for ventilators and other personal protective equipment in parts of the United States. Having a supply chain that is instantaneously reconfigurable and adaptive will provide the agility to respond to scenarios like this in ways considered previously impossible. In scenarios where geographic regions are affected by localized emergencies, such as wildfires, and that region's ability to manufacture is compromised, a fully distributed network could help compensate for localized shutdowns, keeping the flow of goods moving with, what is in essence, a self-healing supply chain.

While these additive production sites could easily exist in urban environments, there is a tremendous opportunity for regional economic and workforce development by bringing such production sites to rural areas, as well. Additive manufacturing requires skilled labor that is readily trainable and encompasses a broad swath of peripheral manufacturing trades beyond running the machines. Examples include: raw material handling and the loading of powder in and out of the machines; the removal of excess powder after the build is complete; the post-processing, stress-relief, and heat treatment of the parts in a furnace and/or other post-processing equipment; the removal of the parts from the build plate; and any final machining. Advanced technical and engineering jobs support those functions as well as the design, modeling, and testing of digital files for additive manufacturing and would provide high-skill job opportunities around the country. Each production site would additionally require management, planning, logistics support, materials sourcing, quality control, and maintenance personnel to support the additive manufacturing process. Local community high schools, colleges, public and private universities, and trade unions can be utilized for the recruitment and training of the workforce, while internships and direct recruitment can be exercised by the production sites themselves.

While the flexibility of additive factories is what will enable them to be brought to rural areas, it is the economic advantage of manufacturing products close to their point of need that will keep them there, as well as the workforce they employ. Transportation costs and its environmental impact will be reduced. By creating the ability to make a virtually limitless mix of goods in the local economy, the need for importation will decrease, thereby protecting these jobs from global outsourcing.

The emergence of additive manufacturing networks at scale would drive demand for much stronger digital capabilities throughout the United States to support, manage, and optimize a national network of additive machines, designers, software tools, and digital files. Key requirements includes: (1) digital supply chain capabilities for managing raw materials (including powder supply for the additive factories), parts and products throughout their lifecycle, (2) digital network capabilities for ensuring capabilities to support an exponentially growing need for bandwidth and cybersecurity, including in rural areas, (3) digital multi-factory/multi-machine planning and balancing tools to enable work-sharing and optimization of capacity utilization across a widely distributed network, (4) additive machines and post-processing tools that support the build to standards in order to scale capacity and production efficiency, (5) software and digital AM system capabilities that enable effective and efficient information exchange and collaboration across the network, while safeguarding intellectual property and ensuring cybersecurity, and (6) the continued development of a strong skilled workforce of designers, managers, and operators of additive machines and technology providing new career opportunities in a digital industrial revolution expected to grow rapidly for decades to come.

DIGITAL TECHNOLOGY DEVELOPMENTS NEEDED FOR THE DISTRIBUTED, FLEXIBLE ADDITIVE FACTORY AND SUPPLY CHAIN NETWORK

One of the key technology enablers for a distributed network of additive manufacturing factories is a "digital thread" that allows the continuous collection, linking, and exchange of relevant data throughout the end-to-end manufacturing lifecycle. This includes collecting and linking data within in and across the national network of factories printing the parts, but also includes the designers of parts and developers of the print instructions, to the supply chain of raw materials vendors to the customers receiving the final, delivered parts. Without a digital thread linking data across the additive manufacturing lifecycle, each factory would be operating in the dark, siloed from their supply chains such as materials suppliers and missing out on new knowledge or process improvements developed at other factories. For example, raw powder suppliers typically generate fact sheets that detail the composition of their materials and associated material properties. It is critical that each factory has access to the appropriate materials property data in order to ensure that they will be able to successfully build a particular part. A knowledge base of material properties, part properties, and optimal process parameter combinations should be accessible and updateable by all factories in the same trusted network through a common digital thread.

The digital thread should link data on all parts to the materials used to produce those parts, the specific additive manufacturing machines they were built on, the sensor data generated by those machines, when they were built, what were the process parameters and post-processing used, and so on. This full lifecycle information is extremely valuable for a variety of applications, including performing root cause analysis for identifying and rectifying build issues, reducing waste, and studying variation across builds for continuous process improvement. A complete digital thread can be further beneficial for inventory management, in order optimize when a part needs to be built and when raw material needs to be ordered so that it will arrive in time to complete a specific build job. A fully integrated digital thread is key to enabling just-in-time delivery for effective inventory management up and down the supply chain – suppliers will have visibility to know when a manufacturer might request a raw material, and manufacturers will have visibility into when the supplier will have that raw material available. A digital thread can enable optimizations across the supply chain, leading to operational efficiencies throughout.

Creating a digital thread of the additive manufacturing lifecycle requires linking multimodal data captured in diverse repositories federated across the U.S., including small and big data storage capturing structured and unstructured data types. For example, multimodal data includes relational data, images and videos, binary and other types of files, text, CAD models, time series sensor data, and more. Constructing a digital thread for additive manufacturing can leverage semantic technologies and knowledge graphs to logically link the data in different repositories [9][10]. User-friendly interfaces are critical to get the value out of the data and should sit atop the data stores and provide interfaces that allow users to interact with, explore, and analyze the data without requiring any awareness of where the data is physically located. Such a system would provide a single logical interface encompassing access to a plethora of diverse, distributed data repositories [11].

To achieve its full potential, additive manufacturing demands new integrated algorithms and software for design, build planning, and process simulation. This will allow engineers to exploit the wider "design space" arising from AM's ability to produce highly complex geometries, while ensuring these advanced designs are also producible at high levels of yield and quality. Required design technologies include multi-physics geometry and topology optimization, intelligent part consolidation with consideration of product lifecycle cost/serviceability, and fast design producibility screening tools. Next-generation build planning tools will include optimized build orientation, optimal support generation (or supportless builds, when desired), automated nesting in 2-D and 3-D, and flexible algorithms to facilitate trade-offs between build time, parts per build, support material usage, and post-processing costs. Advanced modeling technologies must include physics-based process simulation of additive builds and post-processing, detection and mitigation of predicted build “crashes,” pre-build compensation for predicted geometric distortion, and highly parallel computation for speed. Advances in machine learning offer the promise of enabling fast simulation and design-build optimization based on surrogate models. Simulation fidelity should improve over time by automatic “tuning” that evaluates model predictions against data from in-situ sensing and post-build inspection. All these capabilities must be integrated and linked to an underlying secure digital thread and data model that enables unambiguous traceability across design, build planning, simulation, build, in-situ monitoring, post-processing, inspection, and back again.

Assuring robust, high-quality additive manufacturing outcomes will also require advanced in-process models, in-situ sensing/ monitoring, and next-generation machine control strategies for additive builds. In-process models and algorithms will optimize additive process parameters relative to local part features and geometry to maintain consistent melt pool configurations. On-machine sensing and control will detect and correct process drift before it leads to build problems. If a local anomaly is detected in a build layer, the process should intelligently adapt to “repair” the problem during the next layer, when possible. If necessary, the repaired region can be tagged for later non-destructive testing and quality assurance. Intelligent modeling, sensing, and control strategies will enable additive machines to correct for thermal or mechanical drift and maintain robust, high-quality process conditions. In the worst case of a severe, uncorrectable machine or process failure, the build will stop to allow for diagnosis and repair, instead of continuing to build for days or weeks before a problem is discovered – sometimes much later – during post-processing or inspection. In-situ data gathered during machine operation can be used over time to calibrate and improve in-process modeling algorithms. In addition, in-process data can reveal trends in individual or fleet machine operating conditions that may suggest changes to operation or maintenance protocols for robust, high-quality production. Low-latency 5G-capable networks will make it possible to off-load processing of this real-time data for centralized analysis and system optimization. This network will be made possible by a secure digital thread, data model, and analytics that maintain traceability and facilitate analysis across models, builds, and datasets.

Current state-of-the-art systems available to both commercial and government operations (such as ERP, PLM, Logistics, and other systems) are increasingly straining to keep up with the numerous challenges and threats to effectively and securely manage and optimize national and global defense and commercial operations. Developing, testing, and implementing new technologies to address these challenges is critical to sustaining and improving design, manufacturing, maintenance, and logistics operations in the future. The need for a more flexible, trusted approach to managing and optimizing digital and additive manufacturing operations on a large scale is apparent. The U.S. Department of Defense is recognizing this need as well and has set into motion a number of initiatives to drive additive manufacturing technology forward [12]. A digital ecosystem for distributed flexible additive manufacturing needs to take into account a complex set of challenges. They include managing the complexity of the additive digital thread from the design CAD file to build file security as well as the on-machine security – all needed to secure the integrity of the build, tracing the impact of the build environment back to the design and build file development, and enabling the protection of intellectual property contained in the CAD files, build files, operator instructions, additive machine operations, post-processing and validation steps, as well as ensuring the security of critical manufacturing process information including equipment status and remote monitoring information.

To effectively address the unique needs of digital and additive design, new digital ecosystems for distributed additive manufacturing have to take advantage of state-

Figure 2. GE's Trusted Additive Manufacturing Network Technology Stack

of-the-art methods, analytics, software, hardware, and communications technology in order to create a system capable of creating and exploiting trusted and distributed information links across one or many networks [13]. This capability can be exploited to develop new approaches to monitoring, controlling, and leveraging assets and information in a distributed network. Underlying this emerging digital/additive manufacturing paradigm are some key philosophies, including 1) compute is effectively free, 2) trust can be digital, 3) trusted decisions can be made at every scale, 4) networks can be secure, and 5) optimal plans and actions can be calculated continuously and in advance as the future unfolds. Building digital additive manufacturing architectures, systems, and applications in this new technology paradigm will be critical to sustaining and improving global supply chain operations beyond the current state of the art.

Traditionally, the heart of the supply chain is trusting the original equipment manufacturer (OEM) to properly manufacture a component. From there, managing (therefore trusting) the supply chain is managing the physical asset. Internet of Things (IOT) devices add digital components (files) and digital processing steps (devices and software) to supply chain risk management (SCRM). This brings into scope what is normally considered IT (and OT) security considerations. However, beyond the traditional concerns addressed by references such as the NIST Cyber Security Framework's Identify, Protect, Detect, Respond, and Recover, IOT devices add, and increase the criticality of, security capabilities such as authenticity and authorization of both human and machine actors, data authenticity or provenance, data integrity, and non-repudiation. IOT devices replace network communication of information initiated by trusted human actors within organizations with IOT device-initiated network communication. GE has been highly involved with developing the security stack using Trusted Computing (Figure 2).

GE's vision is to deploy the trusted stack throughout the entire Edge-to-Cloud Architecture with each of the components depicted in Figure 3 supported by the Trusted Stack mentioned in Figure 2.

To further ensure the integrity of a digital additive manufacturing ecosystem, new cryptographic techniques have emerged that provide protection against quantum threats. These techniques are termed "quantum-safe"

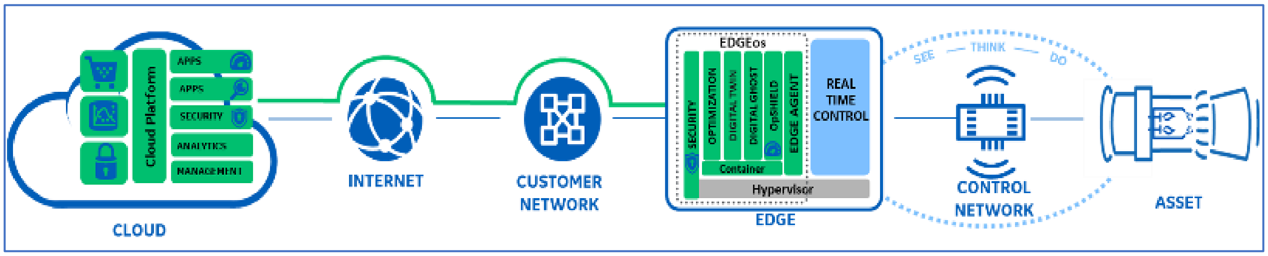

Figure 3. GE Edge-to-Cloud Architecture for Digital Manufacturing

and consist of both techniques based on quantum properties of light that prevent interception of messages (Quantum Key Distribution or QKD), as well as new algorithms (known as Quantum Resistant Algorithms) that are resistant to known quantum attacks, like Shor's Algorithm [14][15].

One key to deriving value from a national network of distributed manufacturing sites is that the sites be remote-native. Not only has the COVID-19 pandemic brought to light the need for industrial facilities to be managed remotely, it has also highlighted the need for fragile supply chains to be replaced by a resilient distributed supply network or supply web that is not just one link away from being broken. While there is certainly benefit for a single site to be remote-enabled, the true potential of distributed manufacturing can be realized when an interconnected system-of-systems can be managed as a whole. For example, digital factory management planning tools that oversee multiple additive manufacturing sites and machines could prioritize and dispatch jobs to specific sites across the network, by match-making regional product needs with local availability of machine time, raw materials, and staff. If isolated sites lack a specific resource (or are shut down completely) the software would be able to dispatch the jobs to neighboring sites and if there are sudden increases in demand, multiple sites could work together to fulfill large orders. A robust digital marketplace could also emerge where sites within the same additive manufacturing network could bid on projects with dynamic pricing that reflects demand. This would provide redundancy and resilience against single-point-of-failure shutdowns, and also would offer the opportunity for individual sites to create niche specializations. Another benefit of having centralized factory management software spanning multiple decentralized manufacturing sites is it would enable skilled tradesmen at local sites to access remote training courses and remote live consulting and troubleshooting. Any knowledge gaps at a particular site could be quickly supplemented such that maintenance and repairs could be fulfilled by local employees with minimal delay.

CONCLUSIONS

A globally competitive U.S. digital and additive manufacturing base will require the design, development, and build-out of a cybersecure digital thread infrastructure. Without cost-effective and trusted data, networks, and systems for digital design, modeling, and transactions, much of the benefit of emerging advanced manufacturing technology will remain limited. Building digital ecosystems for distributed additive manufacturing across the U.S. involving designers, modelers, operators, plant managers, software developers, and many more, requires taking a holistic approach that spans the factory floor to production and network planning and operations. Additive machines are essentially flexible mini factories that can be enabled to contribute individually to local, regional, and national manufacturing networks. To achieve this, however, requires significant investment in new digital networks that can handle cross-machine and cross-factory data flows for visibility, planning, optimization, and execution. This will include, e.g., data on machine availability including build and material capability, machine status through remote monitoring, and visibility into equipment uptime or overall equipment effectiveness (OEE).

To be effective and pervasive, these new systems will need to adopt, to the extent possible, open data and network standards, new cybersecurity technologies for intellectual property and identity to protect commercial interests and national security. And, they will need to be built on high-speed, high-bandwidth, low latency networks (including emerging 5G networks) that can lower the friction in the current digital manufacturing environment, which is hampered by manual, labor-intensive processes across the digital thread including the use of what is essentially a “sneaker net” to move files and work along the process from design modeling and build preparation to additive machines. A national effective digital distributed ecosystem for additive manufacturing has the potential to dramatically change the innovation trajectory, drive newfound efficiencies in digital manufacturing for production and new product and process innovation across the United States.

The capital investment required is significant. High-tech additive machines are relatively expensive, in part due to the still limited volume of operations across the U.S. and around the world. Large-scale investments in additive machines, networked systems, and R&D will create further efficiencies in machine design and production, while increasing capabilities and lowering costs per unit, driving down additive manufacturing costs. To accelerate innovation and the maturation of additive manufacturing technology from R&D to production systems, including in hardware and machines, software and networks, new large-scale public-private partnership investments must be made [16]. These efforts must include further collaborations between the U.S. government, industrial, and academic partners.

Overseas competition in both commercial and defense applications is accelerating and billions of dollars is being driven into additive manufacturing by China and other nation-states. A U.S. national public/private partnership to enable additive manufacturing investment could become the next technological “moon shot” for the U.S. economy with real and direct economic benefits in terms of high-skill employment generation, high-tech technology development, and high-impact national economic and defense capabilities.

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John Carbone is a Principal Engineer and has more than 25 years of experience at GE Research. In his current role, he is leading teams of scientists developing business integration systems based upon blockchain technologies for asset management applications within GE's industrial businesses. Currently, John is developing embedded computing implementations of blockchain technology in the additive manufacturing and electrical industries.

Justin Gambone is the Additive Manufacturing Technology Leader for GE Research. He coordinates the technology development and long term plans for additive machine capability to improve reliability, insights, and cost of additive machine architectures and their use in critical industry markets. He received his masters degree in Mechanical Engineering from Georgia Tech and holds 12 patents related to additive manufacturing.

Dr. Dean Robinson, Ph.D., is a Principal Engineer and Additive Design-to-Build Mission Leader at GE Research, where he has over 35 years of experience. He develops and leads projects in modeling, simulation, and software to reduce the time and cost of taking metal additive component designs from concept to producible geometry and dimensionally correct final parts. He holds 18 patents in advanced manufacturing, with 7 in additive manufacturing, and has ~15 peer-reviewed publications. He received his Ph.D. from Cornell University.

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