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An **Overview** of Additive Manufacturing

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Additive manufacturing (AM)—known also as "3D printing"—has exploded into public consciousness over the past several years. Stories and perspectives seem to appear in the popular press and technology blogs on a near daily basis.

Enthusiasts tout the prospect for AM to revolutionize manufacturing industries and the markets they serve, while skeptics point to the relatively limited number of applications and materials in current use. While the reality of AM likely rests somewhere between these two views, there can be little doubt that the technology is enjoying an increasing deployment across sectors—both within manufacturing and beyond—and throughout all phases of the value chain.

This article provides an overview of AM—its technologies, processes and end-market applications. In addition, we touch upon a number of strategic challenges that companies should consider as they integrate AM into their value propositions. We also offer a strategic framework that may help companies understand how this set of technologies and processes increases flexibility and reduces the capital required to achieve greater scope and economies of scale.

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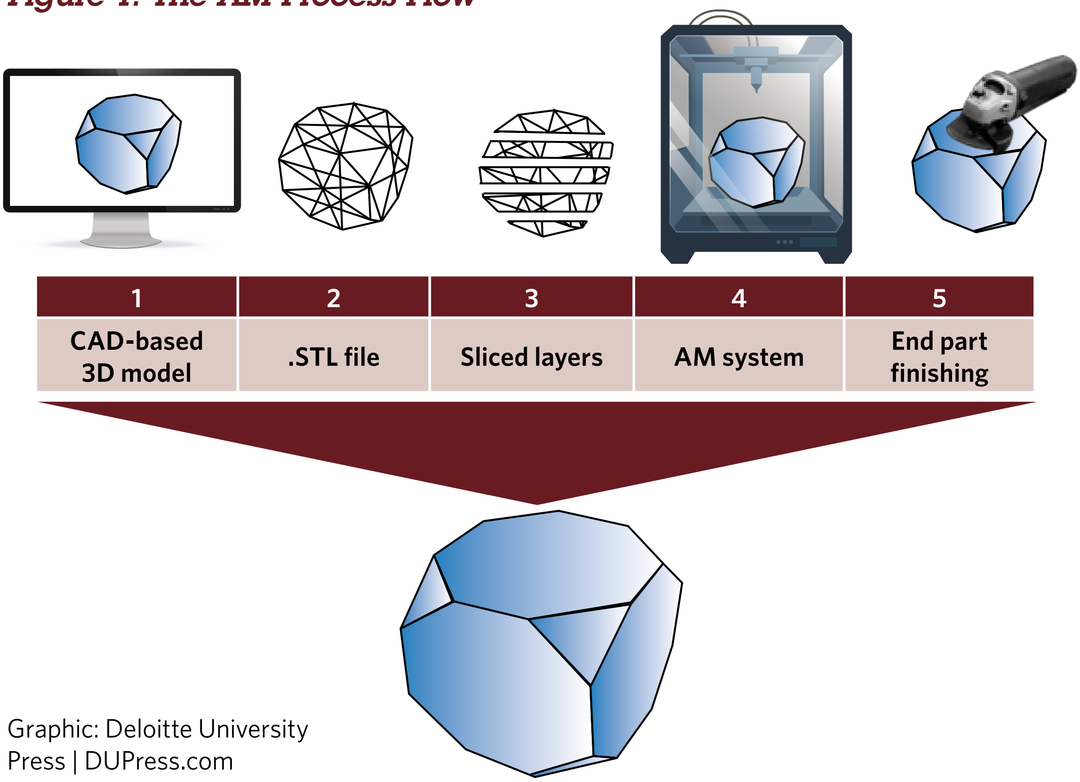
What Is AM?

AM refers to a set of technologies and processes developed over more than 30 years. ASTM International, a global body recognized for the development and delivery of consensus standards within the manufacturing industry, defines AM as: "A process of joining materials to make objects from 3D [three-dimensional] model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies." In common practice, the terms "AM" and "3D printing" are used interchangeably.

Figure 1. The AM Process Flow



Graphic: Deloitte University Press | DUPress.com

Layer by Layer Additive Process

The AM process traditionally begins with the creation of a 3D model through the use of computer-aided design (CAD) software. The CAD-based 3D model typically is saved as a standard tessellation language (.STL) file, which is a triangulated representation of the model. Software then slices the data file into individual layers, which are sent as instructions to the AM device. The AM device creates the object by adding layers of material, one on top of the other, until the physical object is created.

Once the object is created, a variety of finishing activities may be required. Depending on the material used and the complexity of the product, some parts may need secondary processing, which can include sanding, filing, polishing, curing, material fill or painting. Figure 1 depicts the overall AM process.

Sophisticated 3D scanning and imaging tools are emerging as alternatives for traditional CAD programs. In addition, stylus-based and other design technologies that allow consumers to modify digital models themselves—without the need for extensive CAD experience—are expected to contribute to growth in the personal AM systems space. New formats, such as AM file format (AMF), are also being developed to address .STL's limitations and allow for more flexible file structures.

Trade-offs Versus Traditional Manufacturing

AM creates 3D structures by adding materials layer upon layer. In contrast, traditional manufacturing practices (such as drilling or machining) are often "subtractive," as they remove material from areas where it is not desired. AM and

Table 1. Comparative Advantages of AM and Traditional Manufacturing

Advantages of AM	Advantages of Traditional Manufacturing
Design complexity: AM enables the creation of intricate designs to precise dimensions that are difficult or near impossible to create using traditional methods.	Mass production: Traditional manufacturing is well-suited for high-volume production where fixed tooling and setup costs can be amortized over a larger number of units. AM is generally more competitive for low-to-medium volume production runs.
Speed to market: AM systems can manufacture products with little or no tooling, saving time during product design and development—and enabling on-demand manufacturing.	Choice of materials: Traditional manufacturing techniques can be deployed to a wider range of materials.
Waste reduction: AM typically uses less extraneous material when manufacturing components, significantly reducing or eliminating scrap and waste during production. This makes AM a more efficient process.	Manufacturing large parts: Despite advancements in "big area" printing, AM systems are still largely constrained by limited envelope sizes. By comparison, traditional machining is better suited to manufacturing large parts.

Source: Deloitte analysis

traditional manufacturing face different trade-offs, with each process likely to play a role in the deployment of manufacturing capabilities. Table 1 lists some of the respective advantages of AM and traditional manufacturing.

Overall, AM offers companies an array of time efficiencies and cost reductions throughout the product life cycle and supply chain, as well as greater flexibility in design and product customization than traditional manufacturing. These benefits will likely drive increasing levels of AM adoption going forward.

Processes, Technologies and Applications

Functional prototypes and end-use parts built through AM technologies have wide applications in industries such as industrial and consumer products, automotive, medical and commercial aerospace and defense. AM technologies deploy multiple different processes to address issues such as design complexity, surface finish, unit cost, speed of operations, and others. To meet diverse requirements, industrial-grade AM systems are available in the market ranging in cost from less than $10,000 to $1 million—and more.

AM technologies typically are based on one of the seven primary manufacturing processes described below in Table 2. The major AM processes and technologies can be characterized by the materials they use and the advantages and disadvantages they offer (see Table 3).

Although AM material availability is less varied when compared to traditional manufacturing approaches, AM technologies still use a range of materials, including plastics, metals, ceramics and composites, as Table 3 shows. At the present time, plastics (polymers) and metals are most commonly used in AM systems. To a lesser extent, ceramics and composites also support AM processes. Increasing use of varied materials in AM is an area of focus for future research and development.

Inherent Benefits to Increasing Penetration in the Next Decade

Overall, since its beginnings some 30 years ago, AM systems have become markedly faster, more versatile in complexity of design and variety of materials used, and less expensive. At the same time, the global AM products and services industry has seen remarkable growth—from virtually nothing in 1985 to more than $20 billion projected in 2020 according to Wohlers Associates.

Application of AM technologies is expected to grow across industries as increasing numbers of companies use the processes not just for producing prototypes, but to manufacture parts and full-scale products. Such applications will act as a particularly strong catalyst for substantive research developments in the health care and manufacturing industries. Table 4 summarizes some current applications of and potential future developments in AM in select industries. The breadth of

Table 2. AM Major Manufacturing Processes

Vat photopolymerization
A liquid photopolymer (i.e., plastic) in a vat is selectively cured by light-activated polymerization. The process is also referred to as light polymerization.
Related AM technologies: Stereolithography (SLA), digital light processing (DLP)

Material jetting
A print head selectively deposits material on the build area. These droplets most often are comprised of photopolymers with secondary materials (e.g., wax) used to create support structures during the build process. An ultraviolet light solidifies the photopolymer material to form cured parts. Support material is removed during post-build processing.
Related AM technologies: Multi-jet modeling (MJM)

Material extrusion
Thermoplastic material is fed through a heated nozzle and deposited on a build platform. The nozzle melts the material and extrudes it to form each object layer. This process continues until the part is completed.
Related AM technologies: Fused deposition modeling (FDM)

Powder bed fusion
Particles of material (e.g., plastic or metal) are selectively fused together using a thermal energy source such as a laser. Once a layer is fused, a new one is created by spreading powder over the top of the object and repeating the process. Unfused material is used to support the object being produced, thus reducing the need for support systems.
Related AM technologies: Electron beam melting (EBM), selective laser sintering (SLS), selective heat sintering (SHS), and direct metal laser sintering (DMLS)

Binder jetting
Particles of material are selectively joined together using a liquid binding agent (e.g., glue). Inks also may be deposited to impart color. Once a layer is formed, a new one is created by spreading powder over the top of the object and repeating the process until the object is formed. Unbound material is used to support the object being produced, thus reducing the need for support systems.
Related AM technologies: Powder bed and inkjet head (PBIH), plaster-based 3D printing (PP)

Sheet lamination
Thin sheets of material (e.g., plastic or metal) are bonded together using a variety of methods (e.g., glue, ultrasonic welding) to form an object. Each new sheet of material is placed over previous layers. A laser or knife is used to cut a border around the desired part and unneeded material is removed. This process is repeated until the part is completed.
Related AM technologies: Laminated object manufacturing (LOM), ultrasonic consolidation (UC)

Directed energy deposition
Focused thermal energy is used to fuse (typically metal) material as it is being deposited. Directed energy deposition systems may employ either wire-based or powder-based approaches.
Related AM technologies: Laser metal deposition (LMD)

Sources: Deloitte analysis; ASTM International, Standard terminology for additive manufacturing technologies, designation F2792 – 12a, 2013, p. 2

Table 3. AM Technologies—Their Base Materials, Advantages and Disadvantages

Technology	AM process	Typical materials	Advantages	Disadvantages
Stereolithography	Vat polymerization	Liquid photopolymer, composites	Complex geometries; detailed parts; smooth finish	Post-curing required; requires support structures
Digital light processing	Vat polymerization	Liquid photopolymer	Allows concurrent production; complex shapes and sizes; high precision	Limited product thickness; limited range of materials
Multi-jet modeling	Material jetting	Photopolymers, wax	Good accuracy and surface finish; may use multiple materials (also with color); hands-free removal of support material	Range of wax-like materials is limited; relatively slow build process
Fused deposition modeling	Material extrusion	Thermoplastics	Strong parts; complex geometries	Poorer surface finish and slower build times than SLA
Electron beam melting	Powder bed fusion	Titanium powder, cobalt chrome	Speed; less distortion of parts; less material waste	Needs finishing; difficult to clean the machine; caution required when dealing with X-rays
Selective laser sintering	Powder bed fusion	Paper, plastic, metal, glass, ceramic, composites	Requires no support structures; high heat and chemical resistant; high speed	Accuracy limited to powder particle size; rough surface finish
Selective heat sintering	Powder bed fusion	Thermoplastic powder	Lower cost than SLS; complex geometries; no support structures required; quick turnaround	New technology with limited track record
Direct metal laser sintering	Powder bed fusion	Stainless steel, cobalt chrome, nickel alloy	Dense components; intricate geometries	Needs finishing; not suitable for large parts
Powder bed and inkjet head printing	Binder jetting	Ceramic powders, metal laminates, acrylic, sand, composites	Full-color models; inexpensive; fast to build	Limited accuracy; poor surface finish
Plaster-based 3D printing	Binder jetting	Bonded plaster, plaster composites	Lower price; enables color printing; high speed; excess powder can be reused	Limited choice of materials; fragile parts
Laminated object manufacturing	Sheet lamination	Paper, plastic, metal laminates, ceramics, composites	Relatively less expensive; no toxic materials; quick to make big parts	Less accurate; non-homogenous parts
Ultrasonic consolidation	Sheet lamination	Metal and metal alloys	Quick to make big parts; faster build speed of newer ultrasonic consolidation systems; generally nontoxic materials	Parts with relatively less accuracy and inconsistent quality compared to other AM processes; need for post-processing
Laser metal deposition	Directed energy deposition	Metals and metal alloys	Multi-material printing capability; ability to build large parts; production flexibility	Relatively high cost of systems; support structures are required; need for post-processing activities to obtain smooth finish

Sources: Deloitte analysis; Wohlers Associates, Additive manufacturing and 3D Printing state of the industry, 2012; Troy Jensen and Pipar Jaffray, 3D printing: A model of the future, March 2013; Justin Scott, IDA Science and Technology Policy Institute, Additive manufacturing: status and opportunities, March 2012.

current and likely future applications suggests that there is strong growth potential for AM going forward.

Strategic Considerations Going Forward

Some experts have heralded AM as the next great disruptive technology, similar to personal computing, giving everyone on the planet the ability to imagine, design and create custom and personalized products. As powerful and transformational as AM will likely be across an array of industries and applications for years to come, organizations should address a number of strategic challenges as they integrate AM into their value chain. We identify four such strategic challenges as especially worthy of further consideration.

AM Workforce Development

This projected growth for AM, while positive, also brings with it a significant challenge: heightened competition for a finite talent pool with the skills to use this technology. This challenge is expected to affect organizations of all sizes, from start-up to enterprise-level. The constricted supply of skilled AM labor is the result of several factors, which can be broadly categorized into the three key talent areas: recruitment and hiring, train-

Table 4. AM Applications by Select End Markets

Industries	Current applications	Potential future applications
Commercial aerospace and defense	• Concept modeling and prototyping • Structural and nonstructural production parts • Low-volume replacement parts • Complex engine parts	• Embedding additively manufactured electronics directly on parts • Aircraft wing components • Other structural aircraft components
Space	• Specialized parts for space exploration • Structures using lightweight, high-strength materials	• On-demand parts/spares in space • Large structures directly created in space, circumventing launch vehicle size limitations
Automotive	• Rapid prototyping and manufacturing of end-use auto parts • Parts and assemblies for antique cars and race cars • Quick production of parts or entire vehicles for the entertainment industry	• Sophisticated auto components • Auto components designed through crowdsourcing
Health care	• Prostheses and implants • Medical instruments and models • Hearing aids and dental implants	• Developing organs for transplants • Large-scale pharmaceutical production • Developing human tissues for regenerative therapies
Consumer products/ retail	• Rapid prototyping • Creating and testing design iterations • Customized jewelry and watches • Limited product customization • Co-designing and creating with customers	• Customized living spaces • Growing mass customization of consumer products

Sources: Deloitte analysis; CSC, 3D printing and the future of manufacturing, 2012.; "US NAVAIR tests 3D printed, safety-critical parts on MV-22B Osprey aircraft", Naval-technology.com, http://www.naval-technology.com/news/newsus-navair-tests-3-d-printed-safety-critical-parts-on-mv-22b-osprey-aircraft-4965373, accessed Aug. 12, 2016.

ing and retention. Recruitment and hiring challenges primarily include accelerated retirement of skilled workers, a generally negative view of manufacturing among members of the Millennial Generation born from the early 1980s until the early 2000s, and an overall lack of science, technology, engineering and mathematics skills in the manufacturing market. For its part, training challenges include the relatively limited number of AM-specific educational programs offered in post-secondary and vocational institutions—no matter how much programs focused on AM are growing in number. Finally, retention of skilled AM professionals presents a challenge precisely because demand is so high for their talents given the limited number of training programs for aspiring AM workers. While many challenges face AM workforce development, organizations can use strategic workforce planning approaches to shape a robust AM workforce and build an AM talent pipeline.

AM Digital Thread

The AM process draws upon a digital design file to deposit material, layer upon layer, to construct 3D-printed parts composed of often complex geometries. Despite their promise and potential, digital designs dictating the production of end-use, 3D-printed objects have not yet moved fully into the mainstream. While AM has become a crucial part of the design process through rapid prototyping and other low-volume applications, it has not reached critical mass for applications in end-use parts and products at the enterprise level. For AM processes to scale at the industrial level, a series of complex, connected and data-driven events is needed. This series of data-driven events is commonly referred to as the digital thread: a single, seamless strand of data that stretches from the initial design concept to the finished part, constituting the information that enables the design, modeling, production, use and monitoring of an individual manufactured part.

This thread enables the flow of data throughout the manufacturing process, including design concept, modeling, build plan monitoring, quality assurance, the build process itself, and post-production monitoring and inspection. The ability to dissect, understand and apply the potentially massive amounts of data and intense computing demands within the digital thread allows users to enhance and scale their AM capabilities and manage the complexities of AM production. Yet, for all its importance, the digital thread is only as useful as it is integrated. Gaps in connectivity or stages within the design and manufacturing process where information remains siloed or isolated in separate parts of the organization prevent the manufacturer from gaining full visibility across the process. Thus, the right digital infrastructure—one that can store, access and analyze vast amounts of data and interoperate across multiple different machines and processes—is crucial to building and operating a successful digital thread.

AM Quality Assurance

While companies have widely explored AM's potential to shrink the scale and scope necessary for manufacturing,

What AM Means for Your Organization: Four Tactical Paths

AM is an important technology innovation with roots going back nearly 3 decades. Its importance derives from its ability to break existing performance trade-offs in two fundamental ways. First, AM reduces the investment required to achieve economies of scale. Second, it can increase flexibility and reduces the funding required to achieve scope.

Investment versus scale: Considerations of minimum efficient scale shape the supply chain. AM has the potential to reduce the capital required to reach minimum efficient scale for production, thus lowering the barriers to entry to manufacturing for a given location.

Investment versus scope: Economies of scope influence how and what products can be made. The flexibility of AM facilitates an increase in the variety of products a unit of equipment can produce, reducing the costs associated with production changeovers and customization and/or the overall amount of equipment and funding required. Changing the investment-versus-scale relationship has the potential to impact how supply chains are configured, while changing the investment-versus-scope relationship has the potential to impact product designs. These impacts present companies with choices on how to deploy AM across their businesses.

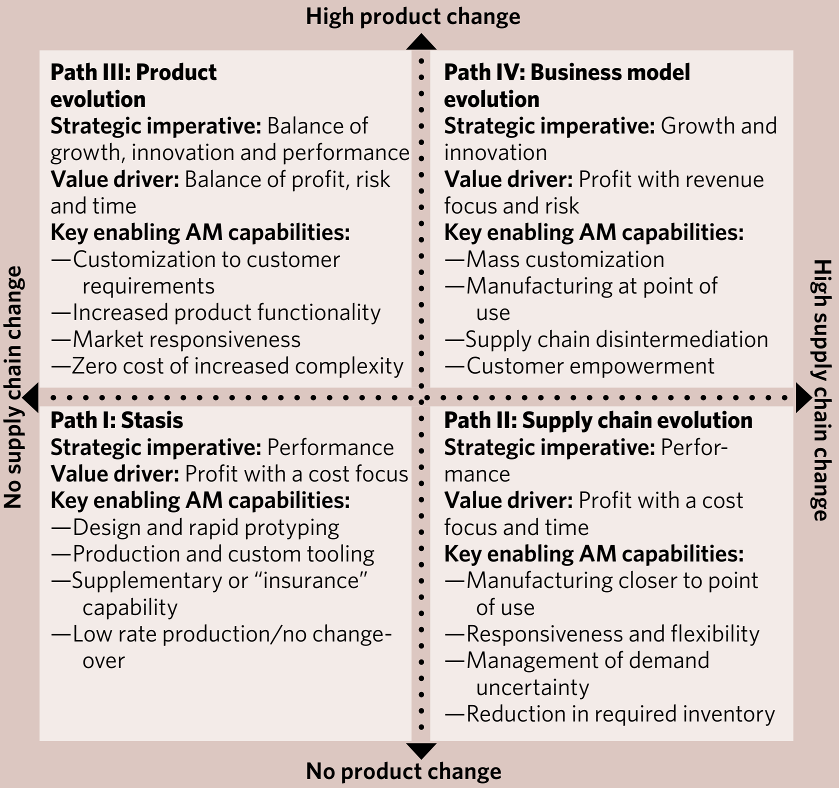
The four tactical paths that companies can take are outlined in the framework below:

Path I: Organizations do not seek radical alterations in either supply chains or products, but may explore AM technologies to improve value delivery for current products within existing supply chains.

Path II: Organizations take advantage of scale economics offered by AM as a potential enabler of supply chain transformation for the products they offer.

Path III: Organizations take advantage of the scope economics offered by AM technologies to achieve new levels of performance or innovation in the products they offer.

Path IV: Organizations alter both supply chains and products in the pursuit of new business models.



Path III: Product evolution
Strategic imperative: Balance of growth, innovation and performance
Value driver: Balance of profit, risk and time
Key enabling AM capabilities:
—Customization to customer requirements
—Increased product functionality
—Market responsiveness
—Zero cost of increased complexity

Path IV: Business model evolution
Strategic imperative: Growth and innovation
Value driver: Profit with revenue focus and risk
Key enabling AM capabilities:
—Mass customization
—Manufacturing at point of use
—Supply chain disintermediation
—Customer empowerment

Path I: Stasis
Strategic imperative: Performance
Value driver: Profit with a cost focus
Key enabling AM capabilities:
—Design and rapid protyping
—Production and custom tooling
—Supplementary or "insurance" capability
—Low rate production/no changeover

Path II: Supply chain evolution
Strategic imperative: Performance
Value driver: Profit with a cost focus and time
Key enabling AM capabilities:
—Manufacturing closer to point of use
—Responsiveness and flexibility
—Management of demand uncertainty
—Reduction in required inventory

Graphic: Deloitte University Press | DUPress.com

produce items based on previously impossible designs, and alter the makeup of organizational supply chains, several significant hurdles prevent its wider adoption. One of the most important barriers is the qualification of AM-produced parts. So crucial is this issue, in fact, that many characterize quality assurance (QA) as the single biggest hurdle to widespread adoption of AM technology, particularly for metals. Put simply, many manufacturers and end users have difficulty stating with certainty that parts or products produced via 3D printing—whether all on the same printer or across geographies—will be of consistent quality, strength and reliability. Without this guarantee, many manufacturers will remain leery of AM technology, judging the risks of uncertain quality as too costly a trade-off for any gains they might realize.

QA presents a multifaceted challenge, encompassing both the scale and scope of production. Indeed, quality doesn't just exist on one dimension; it exists on several from ensuring repeatable quality to guaranteeing quality under any environmental conditions and operational constraints to recognizing circumstances in which quality cannot be guaranteed. Each dimension should be addressed in order for parts qualification—and AM's potential—to be more fully realized.

AM Business Model Considerations

At its core, the AM process is a technical process based on data; without data, nothing gets printed. Yet the very central role that data play in the process of AM value creation inspires consideration of an array of issues that go to the core of the AM business transaction—issues that range from data ownership to data quality to protection of intellectual property rights.

In May 2016, America Makes sponsored a strategic simulation of a procurement action with 80 participants from the Department of Defense and industry. This event highlighted the many varied business model challenges that must be addressed for data to be exchanged enabling AM. For example, these challenges include: product liability, information security and suitable cost and profitability. A chartered working group is addressing these issues, with additional events planned to further explore solutions.

Closing Thoughts

There can be little doubt that the last 30 years have witnessed an unceasing advancement in AM system functionality, ease of use, cost and adoption across multiple industrial sectors. Indeed, there is an unmistakable shift in the AM landscape—from relatively common prototyping and modeling applications toward emerging applications aimed at manufacturing direct parts and end products. If the past is prologue, the role of AM technology in the manufacturing value chain will only grow in scope, scale and complexity. While there is still some time before AM realizes its full potential, companies should assess how AM can help advance their performance, growth and innovation goals.

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MDAP/MAIS Program Manager Changes

With the assistance of the Office of the Secretary of Defense, *Defense AT&L* magazine publishes the names of incoming and outgoing program managers for major defense acquisition programs (MDAPs) and major automated information system (MAIS) programs. This announcement lists recent changes of leadership this year, for both civilian and military program managers, including two for the Air Force that were not reported earlier.

Army

Col. David Warnick relieved **Col. James Romero** as the program manager for the Joint Attack Munition Systems program on July 6.

Col. Troy Crosby relieved **Col. Michael Thurston Mission** as the program manager for the Mission Command program on July 13.

Col. Jonathan Slater relieved **Col. Richard Hornstein** as program manager for the Close Combat Systems program on July 21.

Col. Charles Woshim relieved **Col. Terrence Howard** as the program manager for the Cruise Missile Defense Systems program on July 22.

Navy/Marine Corps

CAPT Casey Moton relieved **CAPT Mark Vandroff** as program manager for the Arleigh Burke Class Guided Missile Destroyer (DDG-51) (PMS 400D) on Aug. 10.

Yeling Wang Bird relieved **CAPT Chris Meyer** as program manager for the Gerald R. Ford Class Nuclear Aircraft Carrier (PMS 378) on Aug. 26.

COL Donald Gordon relieved **COL Rey Masinsin** as program manager for the Command Aviation Command and Control System (CAC2S)(AC2SN) on Aug. 16.

Air Force

Col. John Newberry relieved **Col Christopher Coombs** as program manager for the KC-46A program on Feb. 8.

Col. Brian Henson relieved **Col. Jeffrey Sobel** as the program manager for the Advanced Medium Range Air to Air Missile program on May 27.

Col. Scott Wallace relieved **Col. Douglas Roth** as program manager for the CV-22 program on July 11.

Col. Luke Cropsey relieved **Col. Darren Cochran** as program manager for the GBU-57 Massive Ordinance Penetrator program on July 14.

Col. Paul Rounsavall relieved **John Mistretta** as program manager for the B61-12 Life Extension Program Tailkit Assembly on July 27.

Col. Riley Pyles relieved **Col. Norman Leonard** as program manager for the National Air Space program on Aug. 2.