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Review of Processing Techniques in Large-Format Additive Manufacturing of Polymers and Composites

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1.1 Introduction

Large-format additive manufacturing (LFAM) evolved from the principles of desktop and small-format fused filament fabrication (FFF). FFF systems are rooted in the technology pioneered back in the 1980s, which was commercialized by Stratasys [1]. The key patent for FFF technology, US5121329A, expired in 2009 [2], opening the door for broader innovation and competition in extrusion-based 3D printing.

The leverage of this patent has permitted the growth of this technology as hundreds of companies have started producing their own proprietary systems. This growth has permitted its development and improvement, creating more reliable systems that have generated the conditions for this technology to flourish not only in market share but also in build size, leading to the specific approach of LFAM. The adaptation of pellet screw extruders was crucial in this development, mainly coming from the conventional polymer transformation industry, not without the work of Bellini et al. [3], who in 2005 proposed a precision screw system with continuous feeding. Also, it is important to highlight Volpato et al. [4], who used a piston-driven extrusion in 2015 for polypropylene. Wang et al. [5] in 2016 presented a system called fused pellet modeling (FPM) that was integrated immediately into additive manufacturing. It is important to highlight the research done on screw performance, geometry, and configuration of the systems [6, 7], identifying the optimal shape and configuration to achieve the technical requirements of this approach.

Oak Ridge National Laboratory (ORNL) is widely recognized for pioneering the LFAM platform. Their initial system, known as the “Blue Gantry” due to its distinct, blue-painted weldment, became operational in 2013 (Figure 1.1) [8]. Originally developed to test concrete extrusion devices, the gantry platform was later adapted

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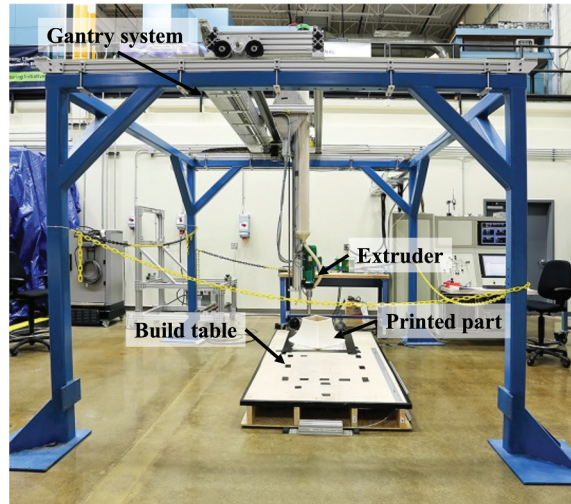


Figure 1.1 Early configuration of the ORNL's "Blue Gantry" LFAM system. Source: Oak Ridge National Laboratory / Public Domain.

for polymer-based LFAM applications. This milestone marked the beginning of a new era in extrusion AM, driving advancements in build size and scalability.

Regarding scalability, desktop FFF systems typically use filament as feedstock, often operate with heated chambers, and are controlled by microcontrollers. In contrast, LFAM systems are designed for industrial-scale production, functioning in open-air environments, and employing programmable logic controllers (PLCs) or other industrial-grade controllers for enhanced precision and durability. ORNL, in developing this technology, has consistently emphasized three core goals: increasing the size ("bigger"), increasing the speed ("faster"), and reducing the cost ("cheaper"). By "bigger," the aim is to expand the physical size and scalability of LFAM systems, enabling the production of large-scale parts and structures that were previously impractical with traditional 3D printing methods. The goal of "faster" reflects a commitment to improving deposition rates and reducing production times, resulting in LFAM being viable for high-throughput manufacturing environments. Finally, "cheaper" focuses on reducing material costs, optimizing energy usage, and enhancing system efficiency to ensure that LFAM becomes an economically viable solution for industries ranging from automotive and aerospace to construction and energy. Achieving these objectives democratizes access to LFAM technology, pushes the boundaries of AM capabilities, and establishes the technology as a transformative tool in modern industrial processes.

When ORNL began developing the LFAM system in 2013, the largest commercially available FFF system was the Stratasys Fortus 900, which offered a build volume of 914.4 mm × 609.6 mm × 914.4 mm (36 in × 24 in × 36 in) [9]. In comparison, common desktop printers like the MakerBot Replicator had much smaller build volumes, typically around 226 mm × 145 mm × 150 mm (8.9 in × 5.7 in × 5.9 in) [10]. While other systems were emerging as new companies entered the market, none at the time offered a printable dimension exceeding 1 m (3 ft) in any direction. For perspective, the total build volume of the MakerBot

Replicator was 4.9 mm^3 (0.000299 in^3), while the Fortus 900 provided 0.51 m^3 (31.104 in^3). In contrast, ORNL's Blue Gantry system introduced a build volume of $2438 \text{ mm} \times 2438 \text{ mm} \times 1829 \text{ mm}$ ($8 \text{ ft.} \times 8 \text{ ft.} \times 6 \text{ ft.}$), offering a total printable volume of 10.87 m^3 (384.5 ft^3). This capacity was more than three orders of magnitude larger than the MakerBot system and an entire order of magnitude greater than the Fortus 900, setting a new benchmark for scalability in AM. The initial implementation of the Blue Gantry, as illustrated in Figure 1.1, featured a fixed plywood vacuum table as the build platform, utilizing build sheets adapted from a Stratasys printer. The end effector was designed to move dynamically across all three axes (-x, -y, and -z), enabling precise deposition across the significantly expanded build area.

To achieve scalability in LFAM systems, filament-based feedstock was replaced with pellet-based materials (Figure 1.2). This shift enables significantly higher throughput, allowing for faster printing speeds necessary for large-scale manufacturing. Unlike traditional systems that use a single heating element in the nozzle, LFAM incorporates advanced extruders with multiple heating elements (Figure 1.2). The extruder system consists of a hopper, where polymer pellets or

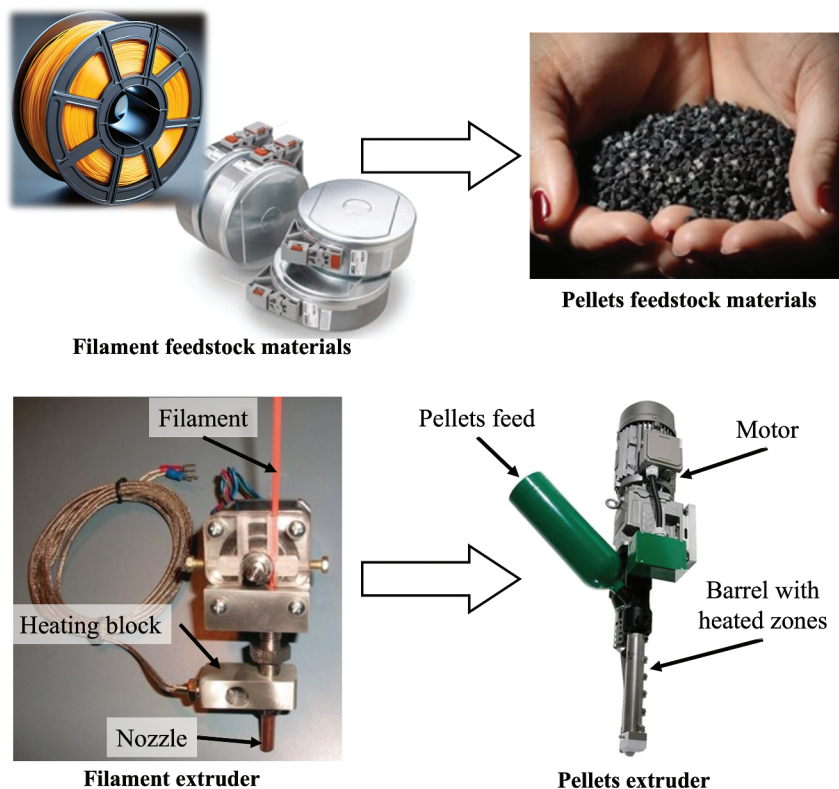


Figure 1.2 Advancing scalability in AM by transitioning from filament-based to pelletized feedstock materials and upgrading from a single heating element nozzle to a multielement pellet extruder. *Source:* Oak Ridge National Laboratory / Public Domain.

powder are fed into a heated barrel containing a rotating screw. The screw plays a crucial role in conveying, melting, and homogenizing the polymer as it moves through different screw zones. The feed zone at the start of the screw picks up the raw material from the hopper and begins transporting it forward. The compression (or transition) zone follows, where the screw channels become narrower, increasing pressure and compacting the material while aiding in melting. Finally, the metering zone ensures complete melting and uniform mixing, preparing the polymer for extrusion through the nozzle. The motor and gearbox drive the screw, while heaters and cooling systems regulate the temperature to ensure proper melting.

These improvements ensure consistent melting and flow of the pelletized material, providing better control over deposition rates and improved material properties. The extruder used in ORNL's Blue Gantry system (Figure 1.2) was an adaptation of a plastic welder from Dohle, repurposed for 3D printing applications. This extruder represented a significant departure from conventional filament-based systems, both in design and functionality. One key feature of the extruder was its swappable nozzles, which threaded into the end of a single-heat-zone barrel. The standard nozzle size was 7.6 mm (0.3 in), a contrast to the much smaller nozzle sizes commonly used in filament-based 3D printers, which typically range from 0.2 mm (0.0079 in) to 0.5 mm (0.0196 in). This increase in nozzle size, more than an order of magnitude, was a critical factor in achieving the higher deposition rates and throughput necessary for large-scale printing. The larger nozzle enabled the extruder to lay down significantly more material in a single pass, reducing printing times while still maintaining sufficient precision for large-format applications. The single-heat-zone barrel, while simpler than modern multizone systems, was designed to effectively melt the plastic pellets used as feedstock, ensuring consistent material flow through the extruder.

Speed has also been a metric that has evolved since 2013, when filament-based 3D printers typically operated at print speeds between 40 and 60 mm/s (approximately 2 in/s). High-speed printers could achieve speeds up to 200 mm/s (approximately 8 in/s), though their reliability was often limited. This was primarily due to poor extruder designs and the absence of advanced control algorithms such as input shaping and linear advance, which are now commonly used to enhance extrusion system performance at high speeds. Initially, these systems operated at an average speed of 125 mm/s (5 in/s) and could reach 250 mm/s (10 in/s) when equipped with command-shaping controls. Figure 1.3 demonstrates a large part being printed at high speed.

While the print speed of these novel developments was comparable to desktop printers like the MakerBot Replicator, the extrusion rate offered a significant advancement. Desktop systems such as the MakerBot Replicator used 1.75 mm (0.069 in) filament and, at maximum speed, could output 15 mm³/s (0.000054 m³/h). Larger desktop systems utilizing 2.85 mm (0.112 in) filament achieved slightly higher throughputs of 20 mm³/s (0.00122 in³/s). In contrast, LFAM systems, equipped with a pellet-fed extruder, delivered an initial extrusion rate of 1105 mm³/s (3,978,877 mm³/h). In 2014, the extruder underwent a major upgrade with the development of a new extrusion screw, designed in collaboration

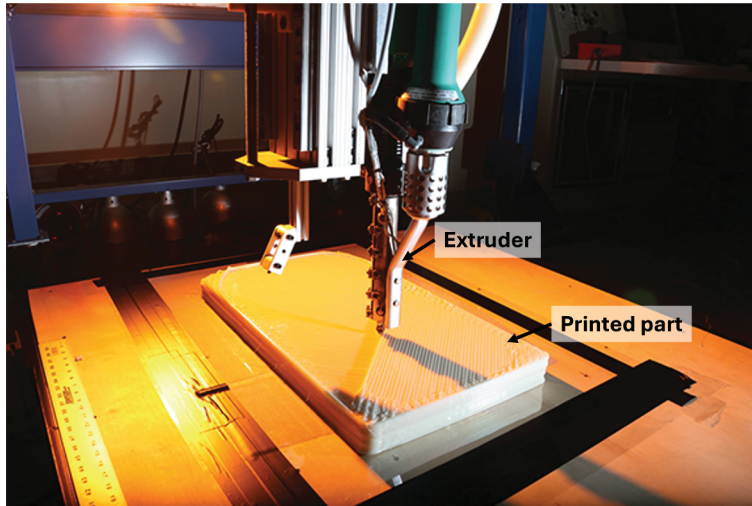


Figure 1.3 A large part being printed on the ORNL's Blue Gantry. Print time is less than two hours for an object too large for other machines to print. *Source:* Oak Ridge National Laboratory / Public Domain.

with Tim Womer & Associates [11]. This enhancement tripled the extrusion rate to $3315 \text{ mm}^3/\text{s}$ ($0.202 \text{ in}^3/\text{s}$), representing a greater than 200-fold improvement over desktop systems available at the time. This throughput translated to a mass flow rate of approximately 13.6 kg/h . (30 lb/h).

Numerous projects and technologies have been developed in the United States with large-scale, pellet-based AM. Of notable significance is the pioneer Big Area Additive Manufacturing (BAAM) technology developed by ORNL in conjunction with Cincinnati, Inc. (Ohio, USA). It has a print volume of about 25 m^3 (882.87 ft^3). With similar functions to the BAAM, Thermwood Inc. (Indiana, USA) developed the large-scale additive manufacturing (LSAM) machine, with a larger size capable of producing 135 m^3 (4767.48 ft^3) parts. This machine can perform additive and subtractive functions (near-net shape manufacturing). It uses a high-volume thermoplastic 3D printer to rapidly create a part and postprocesses it to final dimensions with a five-axis Computer Numerical Control (CNC) cutting head. Currently, the largest project associated with large-format 3D printing has been undertaken by US-based Ingersoll (Illinois, USA), in collaboration with ORNL. The University of Maine commissioned them with the MasterPrint AM machine, which has already been built and sold under the MasterPrint brand, achieving a build volume of 330 m^3 ($11,654 \text{ ft}^3$), also commercialized by Camozzi company in Milano, Italy. Also, Juggernaut3D (Ohio, USA) printers P3-44 series achieve remarkable sizes and results around 1 m^3 (35.315 ft^3) of printing area.

Europe is home to several advanced large industrial printing systems using this extrusion technology. The Delta Wasp 3MT, made by the Wasp company in Lombardy, Italy, has a cylindrical printing volume of about 3 m^3 (105.9 ft^3). Similarly, printers from the Swedish company BLB Industries in Värnamo, Sweden, offer a larger printing volume of 5.6 m^3 (197.8 ft^3). Another LFAM machine has been

designed and manufactured in Spain at the CNC Bárcenas facilities (Valdepeñas, Spain). The first model, Super Discovery Max, features a printing volume of more than 3 m³ (105.9 ft³) and was custom-built for Navantia's 3D Cabins project with the University of Cadiz. In the Netherlands, the CEAD group (Delft, Netherlands) has developed the CFAM Prime, a large-format printer with a 12 m³ (423.8 ft³) milling tool, an extruder capable of reaching 400 °C (752 °F), and a maximum output of 80 kg/h. (176.4 lb/h). This system can also incorporate continuous fibers into extruded polymers at high speeds, reinforcing standard granules with prepreg continuous glass or carbon fibers. The Belotti group (Bergamo, Italy) has introduced the BEAD, a hybrid system with five axes that can print at a 45° orientation. It has a printing output of 80 kg/h. (176.4 lb/h) and can operate at 400 °C (752 °F). Other notable developments include the CMS Creator from the Fraunhofer Institute (Munich, Germany), a hybrid system with a printing volume of nearly 3 m³ (105.9 ft³); the Colossus Mark II from the Belgian company Colossus, offering over 5 m³ (176.6 ft³) of printing volume; and the RD-HUGE from Rev3D (Puglia, Italy), with 14 m³ (494.4 ft³) of printing volume.

1.2 Auxiliary Systems and Equipment Configurations for Enhanced Functionality

This section outlines the auxiliary systems necessary to support successful large-scale AM operations. Additionally, it provides an overview of various equipment configurations, offering a comprehensive perspective on available options to help identify the best fit for specific application requirements.

1.2.1 Material Drying, Conveyance, and Control Systems

While filament materials are generally more expensive, the hardware and systems required to use them are less complex and more affordable. Filament extruders rely on a straightforward mechanism: a stepper motor pushes spooled filament through a heated nozzle. Filament can absorb moisture; this is typically less of a concern because it comes pre-dried in hermetically sealed packaging. Filament is removed from the packaging just before use and mounted near the extruder, allowing it to be consumed before significant moisture absorption occurs. For added protection, some systems store filament in desiccant boxes or ovens during printing, and if filament becomes wet, it can be dried in an oven. In contrast, pellet extruders require a more sophisticated setup, employing a precision-machined screw to shear and melt pellets inside a heated barrel. These pellets, often supplied in large quantities (e.g. in gaylords), must be dried before use (not for all polymer types) because raw resin absorbs moisture from the air. Pellet drying involves more complex equipment. The most common method uses a forced-air desiccant dryer to circulate dry air over a hopper of pellets. Once dried, the pellets are transferred using an automated pneumatic vacuum conveying system, which transports them directly from the dryer to the extruder hopper. Level sensors ensure a consistent supply by maintaining both

the dryer hopper and the extruder hopper full during printing. Once in the extruder hopper, the pellets are gravity-fed into the system for use during the printing process.

While this automated approach significantly improved convenience and efficiency, it introduced additional costs for the necessary components and infrastructure, such as hoses to connect the dryer to the extruder. Moreover, abrasive pellets, like those filled with carbon or glass fibers, can gradually wear down the hoses, leading to pellet loss if not regularly replaced. Despite these challenges, the use of pellet-based systems offers significant advantages in material cost and scalability, making them a critical innovation for LFAM.

1.2.2 Machining and Postprocessing

Machining is a critical step in the LFAM process, particularly as increased throughput and larger nozzle sizes result in greater surface roughness on printed parts. The inherent limitations of AM, such as layer-by-layer inaccuracies and surface irregularities, make post-print machining essential for achieving precise dimensional tolerances and smooth surface finishes. This step ensures that LFAM-produced parts meet both functional and aesthetic requirements, making them suitable for high-performance industrial applications. Systems like Thermwood's LSAM have streamlined this workflow by integrating additive manufacturing and subtractive machining into a single machine. The LSAM features a dual-gantry system, with one gantry dedicated to pellet extrusion for printing and the other equipped with a CNC router for precision machining. This hybrid approach allows for seamless transitions between printing and machining without moving the part to a separate machine, reducing setup time and alignment errors. Several other advanced systems have integrated tool changers to enable hybrid additive and subtractive processes. These systems allow for switching between 3D printing tools, such as pellet extruders, and CNC machining tools. Tool changers are especially important for reducing setup times, minimizing alignment errors, and enabling the production of highly complex parts in a streamlined, automated workflow.

Robotic machining offers flexibility due to its multiaxis capabilities; however, they are inherently less precise than gantry-based systems. This is due to the structural rigidity and repeatability differences between the two designs. Gantry systems rely on fixed linear rails, which minimize deflection and ensure precise positioning of the cutting tool. In contrast, robotic arms have multiple joints that can suffer from reduced stiffness, leading to minor inaccuracies in high-speed or high-force operations. Additionally, they rely on kinematic algorithms for movement, which can introduce cumulative errors in positioning, especially over long machining jobs.

1.2.3 Multimaterials Printing

The multimaterial system addresses the limitations of single-material AM by enabling the creation of structures with varied mechanical and thermal properties. By integrating different materials, such as reinforced polymers, recycled materials,

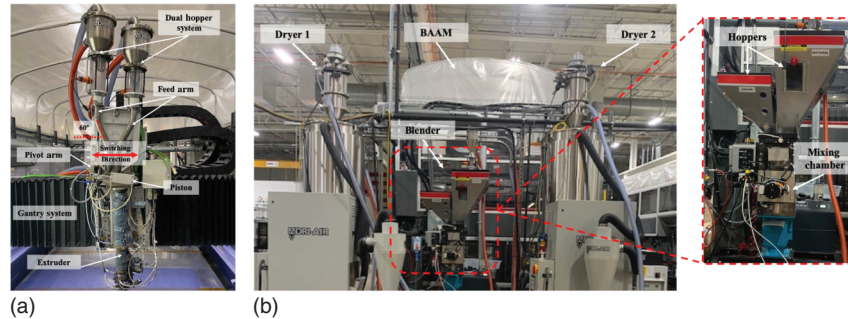


Figure 1.4 Multimaterial LFAM system: (a) BAAM's extruder with a dual-hopper configuration for seamless material switching and (b) BAAM system featuring dual dryers and a blender, with a zoomed view of the blender highlighting the hoppers and mixing chamber for efficient material preparation and blending. *Source:* Smith et al. [12] / U.S. Department of Energy / Public Domain.

or foam, this system supports the production of optimized components for applications like high-strength molds, lightweight turbine blades, and multifunctional structural panels. This capability minimizes material waste during transitions and provides greater control over the final product's properties, making it particularly valuable for industries like aerospace, automotive, and tooling.

Multimaterial printing can be achieved through two primary methods: depositing multiple materials in a single process or utilizing a tool-changing system with two separate extruders. Single-process systems, such as those found in the BAAM platform (Figure 1.4), use a dual-hopper design and a sliding mechanism to switch between materials at the extruder entrance [12]. This approach avoids adding significant weight or complexity to the gantry, enabling hybrid structures like rigid exteriors with lightweight, cost-effective foam interiors. On the other hand, systems with two extrusion setups allow for the use of materials with entirely different heating and melting profiles, which single-process systems cannot achieve. While this method increases system cost and operational complexity, it offers unparalleled flexibility for applications requiring highly diverse material properties.

1.2.4 Pick-and-Place System

The pick-and-place systems integrated into LFAM platforms are designed to automate the embedding of functional components such as sensors, fiducials for postprocessing, integrated heating channels or pipes, and structural reinforcements during the printing process. At its core, the system consists of a pneumatically driven gripper mounted on a linear slide, which allows precise placement of objects into a part mid-print. Components are picked from designated magazines or platforms and strategically positioned within the printed structure as the print progresses. This capability has been successfully implemented in systems like BAAM and Magnum Venus Products (MVP) – reactive additive manufacturing (RAM) thermoset LFAM platforms, see Figure 1.5, enhancing the functionality of printed parts.

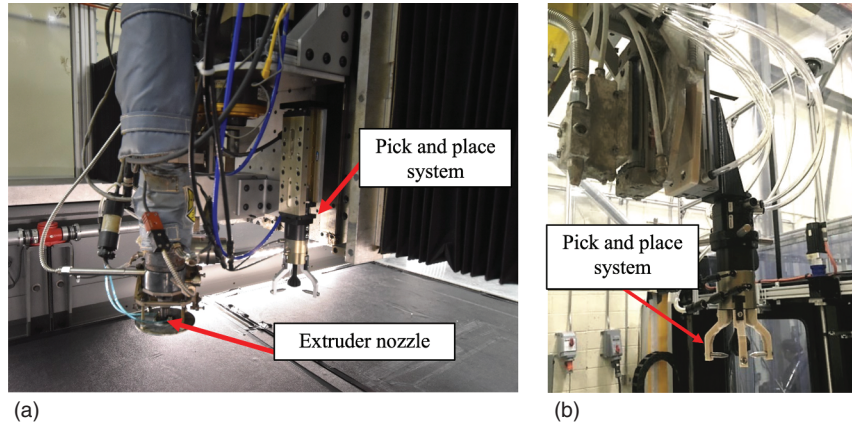


Figure 1.5 Pick-and-place system for integrating sensors, fiducials for postprocessing, embedded heating or cooling channels, and structural reinforcements. (a) Demonstration on BAAM LFAM platforms. (b) Full tool changer assembly showcased on MVP's RAM thermoset LFAM platforms. *Source:* (a) Boulger et al. [13] / U.S. Department of Energy / Public Domain; (b) Boulger et al. [14] / U.S. Department of Energy / Public Domain.

The need for these systems stemmed from the increasing complexity of AM applications, where embedding functional elements during the build process can eliminate labor-intensive postprocessing steps. Traditional methods often require manual alignment or secondary operations, which are time-consuming and prone to errors. Pick-and-place technology addresses these challenges by automating the integration of functional components, reducing production time, and improving accuracy. Additionally, the innovation allows for the fabrication of smarter and more efficient tooling, structures, and end-use parts, making it a valuable advancement for industries like aerospace, automotive, and tooling. The ability to embed sensors, for instance, offers real-time data monitoring during part use, enabling predictive maintenance and ensuring performance reliability.

1.2.5 Heated Enclosures

Research has demonstrated a direct correlation between interlayer bond strength in additive manufacturing and the temperature of the previously deposited layer [15]. This issue arises because lower layers cool below their glass transition temperature (T_g) before subsequent layers are deposited, resulting in weak interlayer adhesion. Maintaining elevated temperatures during the printing process enhances the diffusion of polymer chains across layers, resulting in stronger bonds and improved mechanical properties. To address these challenges, systems equipped with heated build chambers have been developed. These chambers maintain the entire build environment at elevated temperatures, reducing thermal gradients and residual stresses within the printed object. However, implementing large heated chambers introduces complexities, including increased costs and the need for specialized system designs to effectively integrate and protect sensitive electronics and control systems from high temperatures. Industrial-grade systems such as the Juggernaut 3D

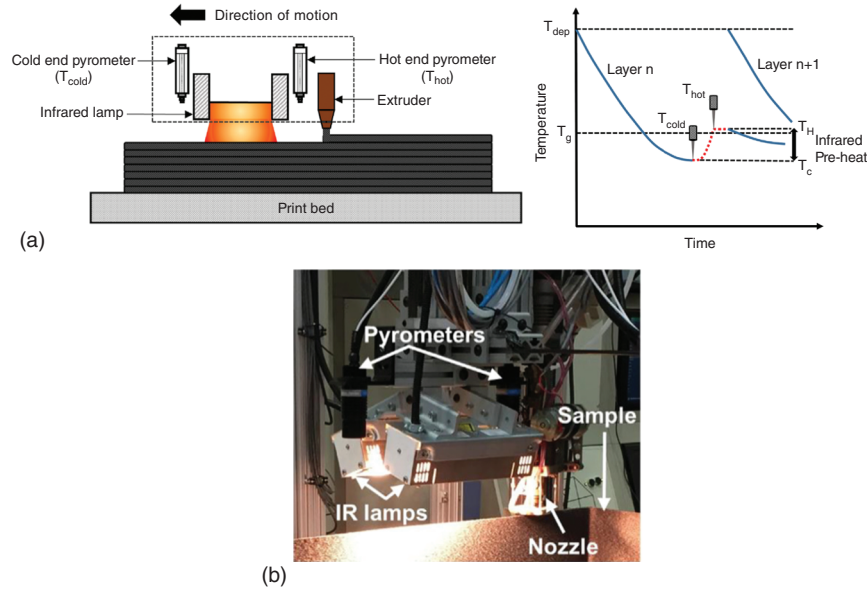


Figure 1.6 IR preheating setup. (a) Schematic representation of the experimental setup and the corresponding time-temperature profile. (b) Key components of the experimental setup, highlighting the integration of the infrared preheating system. *Source:* (a) Adapted from JuggerBot 3D [16]; (b) [16] / JuggerBot 3D.

Tradesman P3-44 [16] and the 3D Systems EXT Titan [17] have incorporated fully heated chambers to expand the processing capabilities for various polymers. By sustaining higher temperatures throughout the build process, these systems enable the use of high-performance materials that require stringent thermal management.

Another way to overcome this is to reheat the previous layer using a device such as an infrared (IR) lamp [18]. This preheating elevates the surface temperature of a printed layer above T_g just before depositing the next layer (Figure 1.6). Experiments were conducted using various IR lamp configurations and print speeds. Results showed that IR preheating effectively improves interlayer bonding, doubling the fracture energy in some cases [18]. However, excessively high IR intensity led to polymer degradation, highlighting the need for optimized heating parameters.

1.2.6 Integration of Automated Fiber Placement

By integrating an in-situ, out-of-autoclave thermoplastic automated fiber placement (AFP) process with advanced LFAM, this approach leverages the high strength-to-weight ratio and inherent toughness of continuous fiber-reinforced thermoplastic composites. Unlike simply adding chopped carbon fiber to thermoplastic, which enhances stiffness but lacks structural integrity, this method uses continuous fibers to achieve superior mechanical properties, offering remarkable strength and stiffness while significantly reducing weight. This synergy of AFP and LFAM not only enhances performance but also maximizes manufacturing

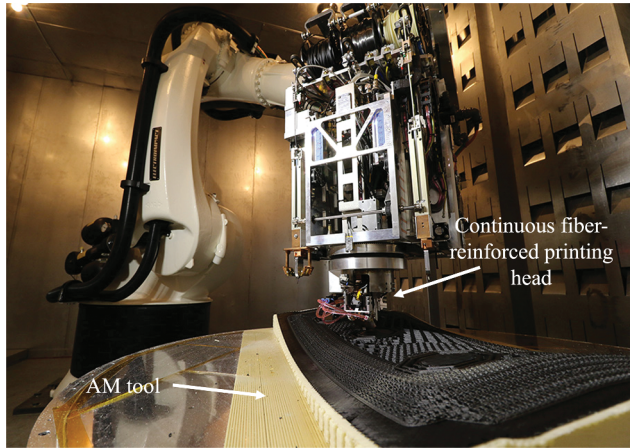


Figure 1.7 Electroimpact's SCRAM system featuring an innovative fiber-reinforced printing head for advanced manufacturing capabilities. *Source:* [19] / Electroimpact Inc.

efficiency and design flexibility. Electroimpact's scalable composite robotic additive manufacturing (SCRAM) system (Figure 1.7; [19]) is an example of this innovation. The AFP process deposits thermoplastic tapes with precise fiber orientation and consolidation, eliminating the need for traditional autoclave curing. When integrated with the LFAM process, SCRAM enables the creation of hybrid structures with optimized strength, weight, and performance characteristics in a single, automated workflow. This combination addresses significant challenges in traditional composite manufacturing, such as high costs, lengthy production times, and dependence on autoclave infrastructure. By overcoming these limitations, the SCRAM system enhances scalability while preserving high material performance. It enables the production of complex, lightweight components with continuous fiber reinforcement for structural integrity, coupled with AM's advantages of rapid prototyping and material efficiency. This hybrid approach minimizes waste, accelerates production, and increases design possibilities, making it a good solution for industries such as aerospace and high-performance automotive, where performance, cost-effectiveness, and innovation are essential.

1.2.7 Coextrusion of Wires

The coextrusion system developed for LFAM integrates a specialized wire embedding tool with BAAM and Ingersoll platforms to produce self-heating composite structures [20]. This system allows for the integration of wires during the printing process for purposes such as heating, reinforcement, or sensing, without disrupting the workflow. The setup comprises a standard pellet-fed extruder, a coextrusion tool, and a specialized nozzle modified for simultaneous deposition of thermoplastic material and wires, with mechanisms for cutting and anchoring the wires in place. During the printing process, the thermoplastic material is extruded to form each layer, while the coextrusion tool embeds nichrome resistance wires precisely within

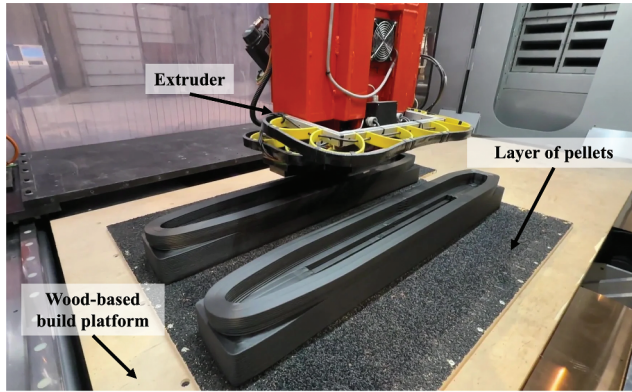
the printed layers. These wires are strategically placed and connected to external power sources to achieve uniform Joule heating across the structure's surface. The slicing software is designed to selectively position the wires in specific layers and locations, enabling targeted functionality. This eliminates the need for traditional external heating methods like ovens or autoclaves, significantly streamlining the production of high-performance composite molds (more information in Chapter 4). This approach is particularly valuable for industries such as aerospace, wind energy, and tooling, where the demand for lightweight and cost-effective composite molds is critical. Also, Nikki L. Martinez from UTEP has developed an automated ultrasonic wire embedding process for use with material extrusion additive manufacturing and rapid electronics fabrication [21].

1.2.8 Continuous Fiber Printing

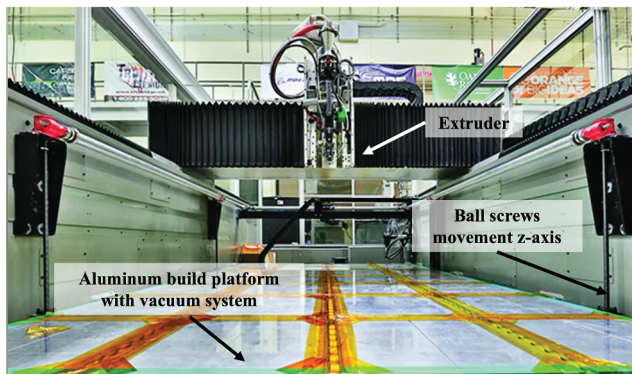
Continuous fiber printing enables the manufacturing of parts with high strength-to-weight ratios and tailored mechanical properties. This process involves embedding continuous fibers, such as carbon or glass, within thermoplastic or thermoset matrices during the printing process. The precise placement of these fibers enhances structural integrity, making continuous fiber printing a preferred choice for high-performance applications [22]. Companies like Orbital Composites are integrating multiaxis robotic systems with AM to create complex geometries and large-scale structures. Their approach allows for fiber reinforcement along optimal load paths, resulting in components that are not only lightweight but also highly durable. Similarly, Continuous Composites has developed continuous fiber 3D printing (CF3D) [23], which combines fiber reinforcements with thermoset resins to produce high-performance composite parts with minimal material waste. This method is particularly advantageous for industries like aerospace and automotive, where material efficiency and performance are paramount. Arevo further pushes the boundaries of continuous fiber printing with its direct energy deposition (DED) machines. These systems utilize continuous carbon fiber and thermoplastics to achieve true 3D paths and z-direction reinforcement, offering superior part strength and rigidity. Arevo's technology has been successfully demonstrated in applications like the Superstrata eBike, showcasing the potential of continuous fiber printing for lightweight and structurally optimized consumer products [24].

1.2.9 Build Table

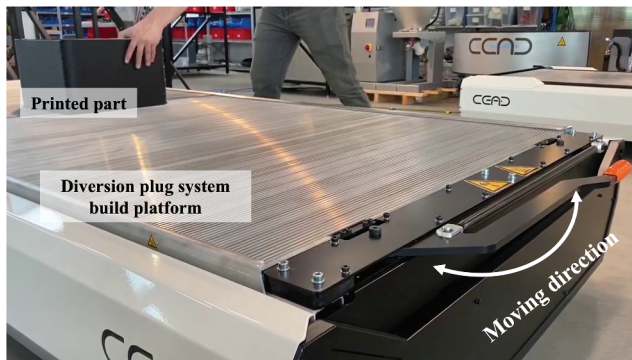
The initial Blue Gantry developed at the ORNL system used a plywood build platform with an unheated surface. The plywood table lacked the ability to heat the initial layers of the printed object, which was becoming a standard feature in desktop 3D printers to prevent warping. Furthermore, the tolerances of the plywood were not as precise as needed. The inherent softness and compliance of the plywood led to significant variations in the first layer, in some cases, compromising print quality and consistency. It is important to note that some Thermwood's LSAM systems still use a wood-based build platform layered with pellets, offering both practicality and cost efficiency (Figure 1.8a). The pellet layer provides a nonadhesive cushion, simplifying



(a)



(b)



(c)

Figure 1.8 Different designs of build platforms. (a) Thermwood's LSAM systems utilizes a wood-based build platform layered with pellets. (b) BAAM's system aluminum build platform with vacuum-assisted system to secure a build sheet. (c) CEAD's patented flat aluminum platform with diversion plug system. *Source:* (a,b) Oak Ridge National Laboratory / Public Domain and (c) CEAD Group / https://www.youtube.com/watch?v=m_vgdi_ueA / last accessed March 14, 2025.

part removal and protecting the platform. This combination reduces wear and allows easy replacement at a low cost.

The BAAM system evolved and incorporated a newly designed aluminum heated build platform for enhanced performance and functionality (Figure 1.8b). To further enhance functionality, ball screws were added at all four corners of the table, enabling precise movement along the z-axis (layer-to-layer direction). Rollers were also integrated into the design, allowing the aluminum plates to be easily rolled on or off when the table was lowered to the ground, streamlining workflow and improving usability. A pneumatic vacuum system was employed to secure a build sheet to a new aluminum build platform by drilling a vacuum port into the underside of the platform and attaching an airline. A metal screen was placed on top of the platform to distribute the vacuum evenly, with the build sheet affixed over the screen and its edges sealed using cleanroom tape. Silicone heat mats were attached to the underside of the aluminum plate, enabling uniform heat distribution across the surface. This addition ensured that the first few layers remained warm, minimizing warping and improving adhesion. In addition to the fixed table configurations, Thermwood also offers the LSAM-MT (moving table) model. This system features a moving table measuring 3.0×3.0 m (10×10 ft approximately). The moving table design allows for sequential printing and trimming operations, although not simultaneously.

CEAD (Delft, Netherlands) features a patented print bed that comprises a rigid frame topped with a flat aluminum plate. This aluminum plate can be heated up to 120°C (248°F). A unique aspect of this print bed is an innovative diversion plug system. This system utilizes consistent hooks made from the printing material itself to anchor each print securely, providing reliable locking throughout the printing process. These hooks are created with rotating blades that trap the material once rotated. Despite the firm grip during printing, parts release effortlessly post-print, facilitating easy removal and reducing the risk of damage to both the printed object and the print bed (Figure 1.8c).

Designing a build table for LFAM requires careful consideration of factors such as thermal management, structural stability, and material compatibility. Key design elements include incorporating a heated surface, ensuring precise flatness, vacuum ports considerations, slots for clamping, and selecting materials that can withstand repeated thermal cycling to list a few. For further details, refer to [25].

1.2.10 Improving Layer Adhesion

In the early days of LFAM printing, before advanced slicing and tool-pathing technologies were developed, challenges such as overfill and extrusion tails, material dragged up when the extruder traveled between locations without printing, often caused significant print defects. Excessive overfill posed a risk of collisions with the hardened material, potentially damaging the system. Initially, this issue was addressed manually with operators using spatulas to level material that rose above the intended layer height. However, this method required constant human oversight throughout the printing process.

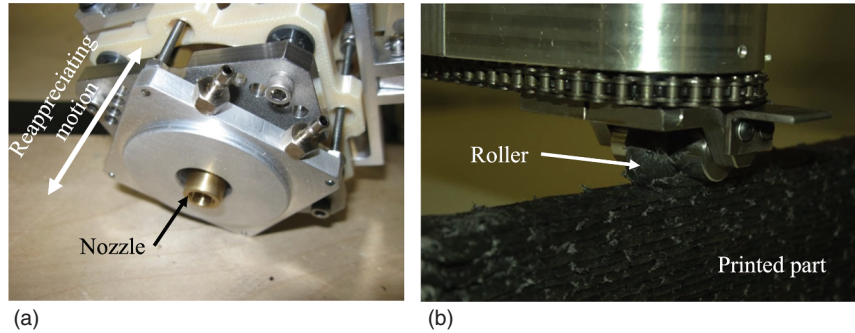


Figure 1.9 Bead compaction system. (a) Tamper with reciprocating linear movement (up and down) to flatten and compact layers, enhancing z-strength. (b) Thermwood LSAM's roller, which follows the nozzle during printing, rotating to compact the extruded material for improved layer adhesion. *Source:* (a) Oak Ridge National Laboratory / Public Domain and (b) Thermawood Corporation.

To automate this task, ORNL developed a device known as the “tamper,” shown in Figure 1.9. The tamper both flattened and compacted the layer and compacted to enhance z-strength. It featured a reciprocating, air-cooled, annular platen surrounding the nozzle, which rapidly moved up and down to apply compaction and leveling force to the extruded bead. Another approach to bead compaction, first implemented by Thermwood's LSAM, is the use of a roller (Figure 1.9). The roller follows the nozzle during printing, rotating behind the bead to compact the extruded material. Compared to the tamper, the roller is mechanically simpler with fewer moving parts, but its effectiveness can be limited in certain geometries, such as sharp corners. Rapid rotations at corners can smear the molten plastic, though advancements in articulation and movement control have improved its efficiency in these situations. The roller's fixed height design provides increased rigidity and enables a greater downward compaction force. Variations of the roller have since been adopted by other companies, further refining this approach to bead compaction.

1.2.11 Slicing Software and Printing Algorithms

Software development for LFAM systems generally falls into two primary categories: control software and slicing software. Control software encompasses the controller firmware and human-machine interface (HMI) software, typically developed by the original equipment manufacturer (OEM) and tailored to specific machines. While ORNL initially developed general control methodologies applicable to multiple systems, most proprietary control solutions now reside with the manufacturers as trade secrets. In contrast, slicing software is often machine-agnostic and has evolved independently over time.

Early control development for LFAM, such as that deployed on the Blue Gantry, was implemented using Matlab and Simulink, with a TargetLink computer providing real-time data output. This setup was effective in a research environment, enabling rapid development and testing of new control algorithms, such

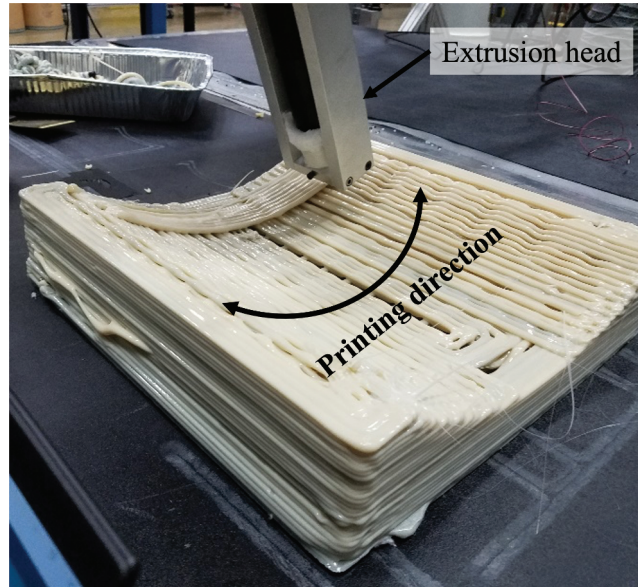


Figure 1.10 Initial testing of a fourth printing axis at ORNL, made possible through advanced control methods and systems. *Source:* Oak Ridge National Laboratory / Public Domain.

as command shaping, and facilitating the creation of necessary HMI controls. It also allowed for quick integration and testing of hardware innovations, such as the fourth control axis (Figure 1.10). However, this Matlab-based approach is less practical in industrial applications, where flexibility and reconfigurability are not as critical as stability and ease of deployment.

Later systems transitioned to using PLCs for machine control. The advanced capabilities of the PLCs supported real-time compensation of the extruder axis based on the motion of the gantry axes, a technique known as extruder servoing. This feature is essential for maintaining accurate bead geometry during acceleration and deceleration, particularly at corners, because pellet extruders cannot accelerate or decelerate as quickly as the gantry. This limitation arises from the fact that pellet extruders are not positive displacement systems like filament extruders. Positive displacement systems, where input is directly correlated to output, allow precise control by guaranteeing a specific amount of material exits the nozzle when a set amount is fed into the hot end. Pellet extruders can achieve positive displacement with the addition of a melt pump, which uses gears to meter extrusion precisely, as in LSAM systems. However, melt pumps add weight and complexity, as well as a tendency to degrade reinforcing fiber length during extrusion. Despite this, melt pumps remain an option for applications requiring extremely precise material control. Currently, most LFAM systems have adopted PLCs paired with custom HMI software to meet the demands of industrial environments. Today, a wide range of controllers is commercially available, including those from manufacturers like Yaskawa and Siemens, offering robust and adaptable solutions for LFAM systems.

AI Build company (London, UK) presents one of the most remarkable solutions not only for LFAM printing systems but also for its combination with milling. The latest version V3, presented this year 2024, offers mainly an automated workflow, which can accelerate and automate multi-axis toolpaths, capable of switching from additive to subtractive process with strategies specifically made for AM. The characteristic that distinguishes them is the automated quality control that combines sensors with AI algorithms analyzing the process in real time, generating reports and analytics to understand the characteristics of every specific part.

Control software and machine firmware are essential for executing 3D printing commands, but slicing software is the key to generating those commands from a CAD model. Slicing software translates a model into machine-readable instructions, or g-code, required for printing.

At the start of the Blue Gantry project, no commercial slicing software existed for LFAM. Early prints relied on g-code from a third-party OEM using proprietary slicing software. Open-source tools like Cura (C++) and Slic3r (Perl) were available but designed for desktop filament printers. Configuring them for large build volumes and complex models often caused crashes or unusable toolpaths. Repetier Host slicer from Hot-World GmbH & Co (Willich, Germany) also offered slicing features but eventually became closed source. ORNL initially modified the open-source slicing software Slic3r™ but encountered frequent failures, with slicing taking up to 24 hours and yielding fragmented results. In response, ORNL developed a custom slicing package. Using a C# interface and a C++ toolpathing engine inspired by Cura from Ultimaker (Utrecht, Netherlands), the new slicer was operational by mid-2014. It reduced slicing times to under 10 minutes and introduced critical features for pellet extrusion, including tip (nozzle) wipes, Revolutions Per Minute (RPM) control, spiral lifts, and I/O integration for auxiliary tools like tampers and powder dusters. By 2020, ORNL released Slicer 2 [26], featuring redesigned data structures for advanced toolpathing and closed-loop printing control. This updated software, available under an open-source license, continues to support LFAM systems.

Since the development of ORNL Slicer, open-source slicing programs including Cura and PrusaSlicer (formerly Slic3r) have seen significant growth and development. These programs have the ability to implement postprocessors and scripts so that their output is more user-friendly for pellet-based extrusion, but many of the fundamental path planning algorithms do not exist because they are not critical for filament printing. Two commercial solutions have been released to bridge the gap between filament and pellet-based extrusion. AI-Build offers advanced toolpath generation designed for AM and subtractive operations on robot-based platforms with integrated AI optimizations. Likewise, AdAxis (Bayonne, Francia) has released the AdaOne software which is focused on advanced AM pathing solutions including nonplanar and five-axis printing [27].

There is a critical need to develop diverse path planning algorithms to improve print quality, increase speed, and optimize the AM process. For instance, these algorithms are applied in areas such as toolpath optimization, adaptive layer height control, and thermal management during printing. Kim et al. have developed and implemented a continuous toolpath generation method specifically tailored

for lattice geometries in LFAM [28, 29]. The need for this development stems from the inefficiencies associated with conventional toolpathing methods, where isolated paths and frequent starts and stops lead to increased printing time, material waste, and reduced layer adhesion quality. This method utilizes a mathematical algorithm that solves the Chinese Postman Problem (CPP), ensuring that the extruder traverses the entire toolpath with minimal movement while depositing material continuously. By generating a seamless Eulerian path through strategic toolpath optimization, the algorithm minimizes the extruder's travel distance, effectively halving deposition time compared to traditional methods. This enhancement enhances productivity while reducing defects such as nozzle oozing and material drag during nonprinting movements. This improvement was validated in applications such as wind turbine blade core fabrication, where layer deposition time was a critical factor.

While filament systems are positive displacement, meaning the amount of material coming out of the nozzle can be directly correlated to the amount of filament being pushed into the nozzle, pellet systems are not. This creates many control issues for maintaining precise and consistent deposition. Advanced calibration and inspection systems, like the Bead Characterization System on the JuggerBot 3D Tradesman [30]. Traditional g-code methods rely on hardcoded parameters for extrusion rates, which must be recalibrated and resliced whenever the material or machine configuration changes. This process is time-consuming and heavily dependent on operator expertise. To better control the process, the machine needs more knowledge of what is expected from the build, which means the slicer needs to pass more geometry information to the 3D printer. This can be done by modifying the g-code output to command the bead width cross-sectional area rather than a fixed RPM [31]. With this advanced slicing functionality, a part can be sliced agnostic of material and printed based on machine-specific calibration data, thus minimizing the amount of information needed during slicing. By transmitting bead geometry parameters, such as cross-sectional area and bead width, instead of extrusion rates, the machine calculates optimal feed rates and extrusion settings in real-time based on prestored calibration data. This eliminates the need for frequent reslicing and recalibration, significantly reducing manual labor and enhancing process flexibility.

1.3 Cost Efficiency, Industrialization, and Market Adoption

The original MakerBot Replicator was priced at approximately 2K USD, catering primarily to homeowners and hobbyists. Lower-cost options, such as the Solidoodle 2, were available for as little as 500 USD, making desktop filament printers accessible to a broad audience. In contrast, larger filament-based FFF systems designed for commercial applications, like the Stratasys Fortus 900 Advanced calibration and inspection system, were priced at over 500K USD. The ORNL Blue Gantry system, being a one-of-a-kind research platform, does not have a fixed price. However, its individual components could be procured and assembled for significantly less than 500K USD. One of the key advantages of LFAM systems lies in the substantial cost

savings associated with feedstock. Prior to LFAM, thermoplastic extrusion printers relied exclusively on filament as the raw material, which is produced from pellets. Filament costs ranged from as low as 25 USD/kg for unfilled commodity resins to over 1K USD/kg for high-performance engineering-grade materials. These high costs were largely driven by the additional extrusion process required to convert pellets into filament, which involves precise melting and extrusion to ensure diameter consistency, such as the common 1.75 mm (0.069 in) size. Filament must meet tight tolerance standards, as variations greater than 0.05 mm (0.00197 in) can clog nozzles and ruin prints.

The LFAM system avoided the need for filament by printing directly from pellet feedstock. This approach eliminated an entire manufacturing step, significantly reducing costs and simplifying the process. Furthermore, skipping the filament production stage preserved material properties by avoiding an additional thermal cycle. Pellet feedstock could be sourced for as little as \$2/kg for neat resin, providing a reduction of cost of over an order of magnitude relative to filament. Pellet feedstock also introduced several additional benefits. As a commodity material already produced at scale for extrusion applications, pellets are far more cost-efficient than filament, which is manufactured specifically for 3D printing. Pellets also provide greater versatility, as fibers such as carbon or glass can be easily added to pellets to enhance material properties like strength and thermal stability. This process is far simpler than with filament, where the addition of fibers often results in nozzle clogging or inconsistent extrusion. Moreover, pellet systems demonstrated greater reliability, as they were less prone to the issues that arise with filament being out of tolerance or fiber reinforced.

ORNL's Blue Gantry system demonstrated the viability of LFAM technology, which was the predecessor of BAAM. However, as a Department of Energy (DOE) research laboratory, ORNL could not commercialize or sell the system directly. Instead, the technology needed to be patented and licensed to industry partners to facilitate the development of commercial systems for the industrial market. The first company to adopt and commercialize this technology was Cincinnati, Inc., which launched its BAAM system (Figure 1.4) in collaboration with ORNL in 2014. The BAAM platform, built upon CI's existing laser cutting system, incorporated linear motors for x/y motion capable of speeds up to 5080 mm/s (200 in/s). The first BAAM system featured a build volume of $1829 \times 3658 \times 914$ mm ($6 \times 12 \times 3$ ft), significantly larger than most AM systems of the time. This partnership marked a pivotal step in translating LFAM from a research initiative into a commercial reality. Shortly after the ORNL-CI collaboration began, ORNL partnered with Local Motors (LM) to produce the world's first 3D-printed car using the BAAM system. The project aimed to print the car live at the International Manufacturing Technology Show (IMTS) in September 2014, in front of an audience of approximately 100,000 attendees. The final car design, crowd-sourced by LM, was named Strati. The printing process for Strati took approximately 48 hours and became the first public demonstration of BAAM's capabilities. This successful print (Figure 1.8) garnered widespread attention, showcasing the vast potential of LFAM for large-scale manufacturing. Since the Strati, LFAM technology has been used to produce other notable prints,



Figure 1.11 Cincinnati Inc.'s BAAM system in collaboration with ORNL (build volume of $1829 \times 3658 \times 914$ mm ($6 \times 12 \times 3$ ft)) printing Local Motors's Strati. The system was used to build a Shelby Cobra replica. *Source:* Oak Ridge National Laboratory / Public Domain.

including a submarine, a Shelby Cobra replica (Figure 1.11), and multiple full-sized houses (more details are in Chapter 5).

1.3.1 Market Adoption

The success of ORNL's Blue Gantry paved the way for the development of commercially available LFAM systems with significantly larger build volumes, unlocking new possibilities across various industrial sectors. Following the Strati project, the capabilities and potential of LFAM captured widespread attention (Figure 1.12). This sparked interest from several companies, including Thermwood, BigRep,

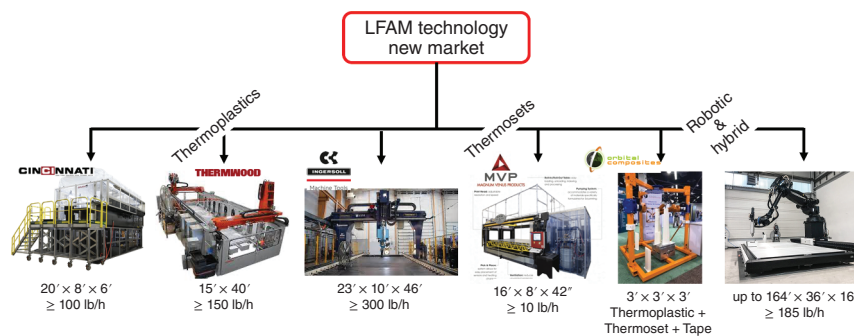


Figure 1.12 Adoption of technology and commercially available LFAM systems with expanded build volumes and deposition rates unlocking new opportunities for innovation across diverse industrial sectors. *Source:* Oak Ridge National Laboratory / Public Domain.

Ingersoll Machine Tools, JuggerBot3D, 3D Platform, and KraussMaffei, which began developing and commercializing LFAM technology. The rapid advancement and adoption of LFAM can be attributed to critical innovations within the academic and commercial sectors. These include breakthroughs in material science, such as enhanced pellet feedstocks and the integration of fiber reinforcements for improved strength and thermal stability. Additionally, advanced motion control systems have enabled greater precision and speed, addressing the unique challenges of large-scale printing.

The growth of LFAM has also fostered the development of a comprehensive supply chain, encompassing material suppliers, machine manufacturers, and end-users. Material suppliers such as Techmer PM, AirTech International, and SABIC; machine manufacturers such as CEAD B.V., Thermwood, Belotti, and Camozzi, etc.; and end-users across various industries, including aerospace, automotive, and construction, have adopted LFAM to produce large-scale components with enhanced efficiency and reduced lead times.

1.4 Choosing the Optimal Motion Platform for LFAM Systems

The current generation of LFAM systems primarily uses gantry robots equipped with high-throughput extrusion systems. With workspaces approaching 50 m^3 (1.765 ft^3), these printers have expanded the boundaries of achievable print volumes while utilizing low-cost feedstocks. However, continued workspace expansion introduces inherent trade-offs, including structural deflection, increased system mass, and higher capital and operational costs [32]. Gantry systems are known for their precision and repeatability, providing an ideal for applications that demand tight tolerances and uniformity. Their rigid frames and linear motion systems provide consistent results, particularly for planar geometries and structured build volumes.

Despite their advantages, scaling gantry systems incur significant penalties, including higher costs per unit volume and reduced efficiency. For example, scaling all three axes proportionally results in increased mass, stiffness requirements, and capital investment (Figure 1.13). While scaling in one direction, such as the x -axis, offers cost advantages, most applications necessitate proportional scaling in all dimensions, requiring advanced control techniques to manage deflection and maintain precision.

On the other hand, robotic systems, while less precise due to joint kinematics, offer greater flexibility and scalability for large or complex geometries. Recent advancements in control algorithms and real-time compensation have narrowed the precision gap, making robotics a viable alternative in specific scenarios. Robotic systems can also be deployed in modular or mobile configurations, enabling adaptive workspaces that exceed the physical footprint of the machine itself. To

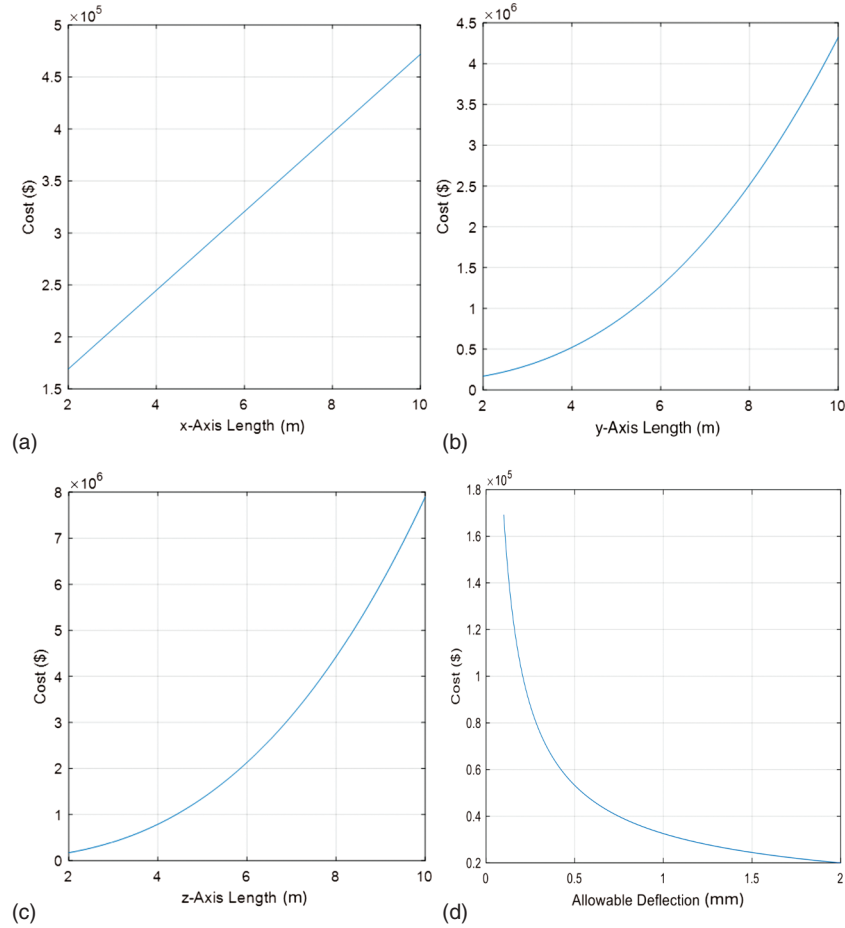


Figure 1.13 Scalability costs of gantry systems. (a) Cost implications of scaling the x-axis. (b) Cost implications of scaling the y-axis. (c) Cost implications of scaling the z-axis and (d) cost impact of increasing allowable deflection. *Source:* Adapted from Roschli et al. [32].

address the challenges of gantry systems, several alternative configurations have been explored [32]:

Track-mounted printers (Figure 1.14a): These systems extend build volume along one axis, typically the x -axis, by mounting a robotic arm or print head on a track [37]. This setup is ideal for producing long, straight parts or consecutive similar components. However, track-mounted systems still face cost challenges, including structural reinforcement for long tracks, and do not address constraints in the other two dimensions.

45°-belt printers (Figure 1.14b): Utilizing a conveyor belt instead of a fixed print bed, these printers achieve infinite build volume along the belt's direction [38, 39]. The 45°-orientation reduces layer times by limiting the profile of each layer to a cross-sectional segment rather than the full perimeter. While effective

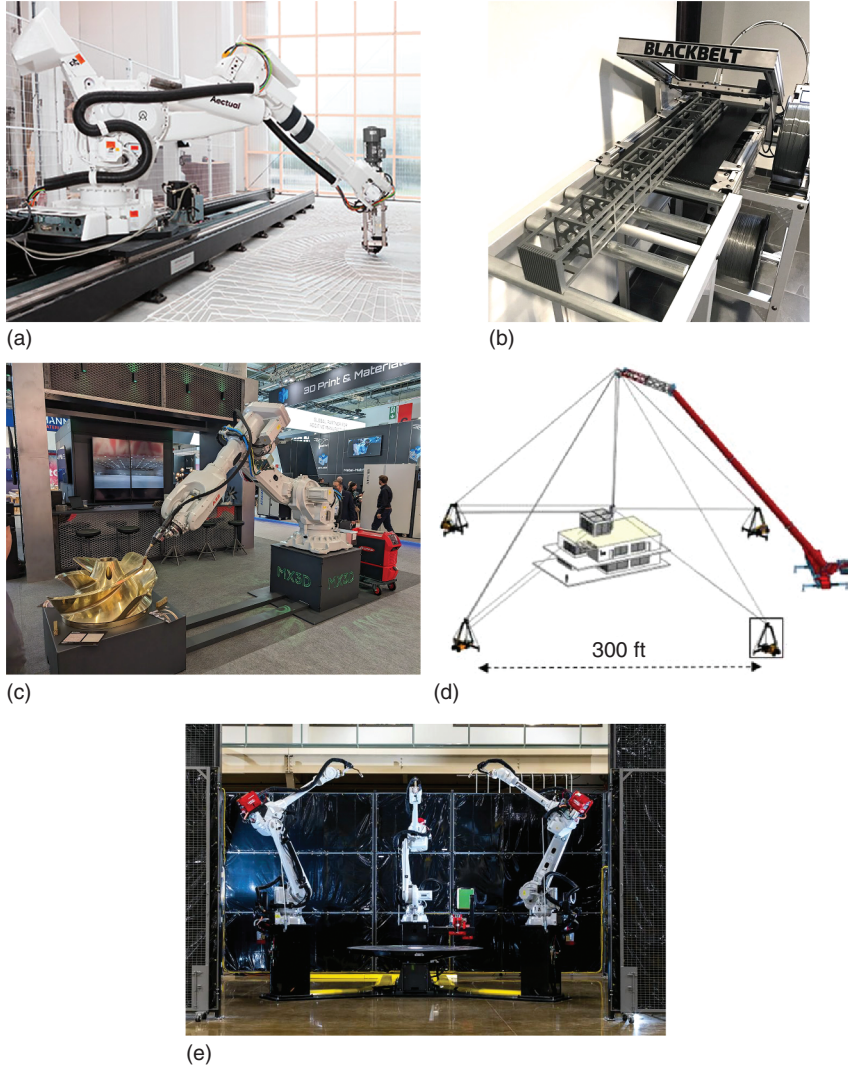


Figure 1.14 Various alternative modular and mobile configurations designed to create adaptive workspaces that extend beyond the physical footprint of the machine itself. These configurations include the following: (a) Track-mounted systems; (b) 45° belt printers; (c) freeform-following printers; (d) cable-driven printing systems; and (e) multiagent printing system. *Source:* (a) Ref. [33] / European Commission; (b) Ref. [34] / BLACKBELT; (c) Ref. [35] / 3D Printing Industry; (d) Chessera et al. [36], Oak Ridge National Laboratory / U.S. Dept. of Energy / Public Domain; (e) Oak Ridge National Laboratory / Public Domain.

for continuous production of long parts, scalability in the other two dimensions is limited, and additional hardware, such as support rollers, may be needed, increasing costs and space requirements.

Freeform following printers (Figure 1.14c): Systems like MX3D [40] use robotic arms mounted on previously printed structures, enabling unlimited

build volumes. This configuration allows for freeform manufacturing, but lightweight or delicate parts may require additional support to handle the robot's weight. Challenges include utility delivery, positional accuracy, and the need for advanced path-planning technologies.

Cable-driven printers (Figure 1.14d): These systems suspend the print head via cables, offering high payload-to-weight ratios and large workspaces. While they reduce the need for large structural components, challenges include workspace optimization, positional accuracy, and scalability in throughput, particularly when multiple systems need to work collaboratively.

Multiagent printing (Figure 1.14e): Multiple robotic arms or mobile platforms collaborate to print large-scale parts. This increases throughput and scalability, but challenges remain in coordination, path optimization, and bonding between sections. These configurations significantly improve productivity but require sophisticated algorithms to optimize path planning and ensure alignment.

The future of LFAM will likely combine traditional gantry systems with innovative configurations such as robotic, track-mounted, and multiagent systems. Convergent manufacturing approaches that integrate advanced AM and subtractive techniques will be critical for achieving scalability and precision. Advancements in control algorithms, material science, and modular system designs will be essential to overcoming current limitations, enabling economically viable solutions.

1.5 Conclusions

The chapter reviews the evolution of LFAM for polymers and composites, focusing on innovations such as the shift to pellet-based feedstock, large build volumes, and auxiliary systems like heated chambers, bead compaction tools, and multimaterial printing. These advancements enhance functionality, scalability, and material efficiency, enabling applications in aerospace, automotive, construction, and tooling. LFAM's ability to produce large, high-performance parts with complex geometries has driven adoption in industries requiring strong, lightweight components. Challenges like scaling costs, structural deflection, and control precision are discussed alongside emerging solutions, such as robotic systems, hybrid AM-CNC (Additive Manufacturing devices assisted with CNC machining in situ) platforms, and advanced control algorithms, which promise to further enhance the economic and technological potential of LFAM.

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