469395

"Barriers to Entry" for Large-Format Additive Manufacturing

Adam Day
Autodesk

Learning Objectives

- What is LFAM and why is it different
- Using Fusion 360 drive robot LFAM
- Strategies for success
- Common difficulties
- Software and equipment

Description

Desktop-scale 3D printing has become ubiquitous in many industries today. As this growth continues, the demand for ever-larger printed parts has increased exponentially. The move to large-format additive manufacturing (AM) is not as simple as just scaling up. Large-format AM delivers a whole new set of challenges not widely understood by the average designer or engineer. In this class, we will demonstrate how to create 3D-printing toolpaths in Fusion 360 software for both typical desktop-scale 3D prints, and large-scale robot-based printing using the new Fusion 360 robot post processor. We will compare and contrast these two workflows and discuss the additional strategies necessary for successful large-format AM. To close the class, we will summarize the three major categories of difficulties faced and how to mitigate them when moving into large-format additive: access to software tools and simulation solutions; process physics and material properties; and machine selection and equipment.

Speaker(s)

Adam Day is a Shop Supervisor at the Autodesk Technology Center Boston, where he empowers resident teams to innovate their design and construction processes using additive manufacturing. Adam has 3D printed projects in a range of scales: from the size of a quarter to a full pedestrian bridge. He also is formally trained and has worked as a landscape architect, wildland firefighter, playground designer, and welder.

What is Large Format Additive Manufacturing (LFAM) and why is it different?

LFAM (Large Format Additive Manufacturing) refers to additive processes that are both large in size and output volume. Generally, LFAM, refers to a printer with a print volume larger than one cubic meter and with an output of more than 2 kg (4.4lbs) per hour. One of the first LFAM printers was the BAAM (Big Area Additive Manufacturing) built by Oak Ridge National Laboratory and Cincinnati Inc. The current BAAM printers had a print bed of 8-foot by 20-foot and a print height up to 6 feet tall (2.5m x 6m x 1.8m). LFAM printers continue to grow in size and capability with recent projects including fully functional boat hulls and car chassis. LFAM refers to printing of polymer pellets but is growing to include a variety of additive processes including metals, ceramics, concrete, and composites.

Differences between LFAM and Desktop scale

Besides the obvious differences in scale between Fused Filament Fabrication (FFF) and LFAM there are also some special considerations.

Feed stock

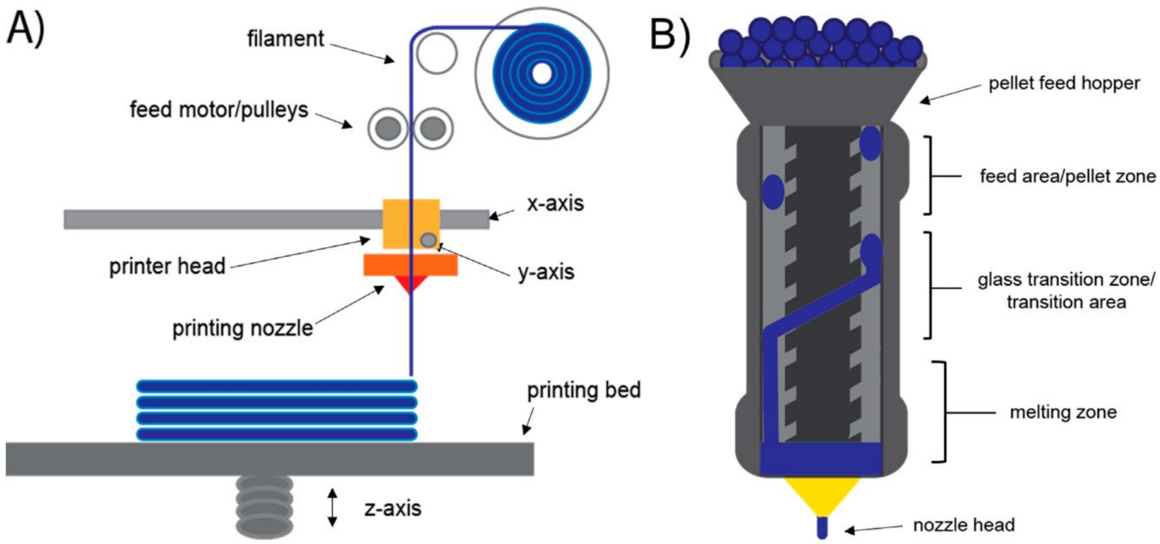
Traditional desktop printers use thermoplastics that have been extruded into a filament and then wound into spools. LFAM printers typically use thermoplastic pellets similar to the material used in injection molding. Using pellets provides many benefits including lower cost, wider selection, and ease of feeding and drying. Many materials designed for injection molding can be adapted for use in LFAM and now suppliers like Techmer, Sabic, and DSM have created custom material mixes just for large format printing.

Throughput

To accommodate the increased size of parts printed with LFAM, the extruders used are capable of flow rates ranging from 2 kg(4.4lbs) to 227kg(500lbs) per hour. This allows parts the size of a car to be printed in a matter of hours instead of day or weeks. To achieve these speeds, pellet feed and drying systems that have been adapted from the injection molding industry are used.

Extruder design/material heating

In filament extrusion, there is a heated area just above the nozzle which heats the filament to a liquid state so that it can be easily extruded and deposited below. In LFAM the feed stock is made of pellets that are fed into a screw which both compresses them and passes them through heating zones to melt the material. The added process of compressing and heating allows the material to reach the print temp faster and allows higher throughput. A side effect of this process is that the extrusion caries a lot more thermal energy and tends to stay hot longer because of the increased mass. This excess heat can cause a whole host of problems. Parts can slump because they do not cool fast enough, and increased stress from the cooling and shrinking can cause warping and delamination between layers.



Lamm, M.E.; Wang, L.; Kishore, V.; Tekinalp, H.; Kunc, V.; Wang, J.; Gardner, D.J.; Ozcan, S. Material Extrusion Additive Manufacturing of Wood and Lignocellulosic Filled Composites. *Polymers* 2020, *12*, 2115

Support structures and overhangs

Because LFAM is currently a single material process, and because of the increased strength of the materials used in LFAM, support structures can be very difficult if not impossible to remove without significant post processing. If you choose not to use support structures, it is very important to design your part so that it does not have overhangs that would cause the printing to fail as gravity pulls the new bead down and it loses contact with the part. Acceptable overhang angles will vary depending on material, geometry, print parameters and re-coat temperature. These parameters should be tested and well understood before designing parts that have significant overhangs.

Feature resolution

Because of the large scale of LFAM printing, the bead width and height are significantly larger than on typical desktop prints. This larger bead size reduces the printable resolution of features that can be made with this process. You should choose a nozzle size which will give you a good balance between minimum resolution and print speed. Smaller nozzles limit the printable width, but also the printable bead height. This is doubly important with LFAM where the material is extremely molten when it comes out so the max height:width ratio is lower than standard FFF. Another option for high precision parts produced with LFAM, is to use a hybrid setup where the part is printed and then machined on the same setup, to achieve both a fast print time and high resolution. It is also important to note that the larger the bead size the quicker the print, but also the worse the surface finish. LFAM parts exhibit a telltale layer stacked surface like FFF but with much larger deviations.

Multi Axis and Hybrid processes

One of the advantages of using robots or large gantry systems is they are also stiff enough to handle the tooling for subtractive operations. It is becoming increasingly common for parts to be printed and then post machined to tolerance on the same setup. This results in parts that are both fast to produce and high precision where necessary. Another advantage of the 6-axis industrial robot arms commonly used in LFAM is that they are not restrained to typical 3 axis toolpaths, and parts can be printed with non-planar toolpaths to improve strength or surface finish.

CEAD AM flexbot 6 axis robot based system. https://cead-am.com/

Printing equipment

Aside from the large print volume, another stark difference between desktop FFF printing and LFAM is the cost of equipment required to get started. While most current desktop FFF systems range from $1000 - $50,000, a fully integrated production ready LFAM system can run in the $250,000 - $1,000,000 range. As the technology is maturing, prices are dropping, and these types of systems are becoming more affordable. On the low-cost end of LFAM you can see research institutions purchasing used 6-axis industrial arms and outfitting them with extruders and other components for around $50,000. These groups rely on the expertise of students and research fellows to do integration of the systems, and design of components necessary to get them fully running.

Benefits of LFAM

The most obvious benefit of the LFAM process is the ability to create a large, fully functional product with complex geometries in a single operation. However, there are many other advantages over small scale and other processes.

Benefits over small scale

- Expanded Design envelope: able to print much large parts in one operation.
- Part consolidation: able to print your design as a single part instead of multiple components which need to be assembled.
- Reduced manufacturing time: ability to print parts more then 200x faster.
- Ease of hybrid process: robot and gantry systems have the stiffness to perform subtractive operations.
- Composite materials: pellet extruders can run composite filled materials with almost no changes other than print settings.

Benefits over other processes (casting, machining)

- Inventory reduction: ability to make parts on demand and not stock spares.
- Waste reduction: uses only the material necessary to make the part.
- Reduced labor: minimized post processing operations such as joining and assembly.
- Reduced cost at specific scales: per part cost can be significantly less for volumes under 1000 because there is no upfront tooling cost.

Using Fusion 360 to drive robotic additive manufacturing

One of the goals of Fusion 360 has always been to connect the entire design to manufacture workflow. In this class we have covered the normal desktop scale 3d printing workflow and compared it to the workflow for large format additive with a robot. Included below are some resources for getting started with Fusion 360 FFF desktop scale 3d printing. These are the foundations for understanding how to use Fusion for LFAM, and you should be familiar with them beforehand.

Introduction to Fusion 360 FFF:
https://www.autodesk.com/products/fusion-360/blog/fusion-360-fff-printing/

Deep dive webinar on Fusion 360 FFF:
https://www.youtube.com/watch?v=v4-d2DUXYbM

The main differences between using Fusion 360 for FFF and for LFAM are the process settings, and the act of post processing for use on a robot. Using Fusion 360 for to control robots will be covered in much greater detail by my colleague Stefany Pender in her presentation: "Learn the rules, then break them: Fusion 360 for Industrial Robot Arms" Class number 467178.

Strategies for Success

Designing for Polymer LFAM

Because of the large amount of material and time invested in printing with LFAM, it is important to design your parts to maximize the chances of success. Design for manufacturing is an important step in every workflow, but it is vital when dealing with new processes such as LFAM where designers may not be able to use intuition gathered from previous works.

Size

Part size is the largest driver for choosing LFAM over other processes. Part size is also the driving factor in almost every other decision in made in design for additive Manufacturing (DFAM). Part size determines which extruders and build plates can be used, which in turn dictates the available nozzle sizes, flow rates, and print times. These can be the deciding factors in making LFAM cost effective for your operation.

Wall thickness and feature resolution

Thin walls and small features should be avoided when possible. The large bead size and difficulty with starts and stops, make these features error prone. When designing thin wall sections, ensure that the thickness is at least 2x the bead width. By using multiples of the bead width, you can ensure that thin walls will be easy to toolpath, and be extruded without gaps or overlapping.

Orientation

While part orientation is important in desktop scale 3d printing, it is even more important in LFAM because of the difficulty with support structures, and the lack of removable support materials. Both FFF and LFAM printing exhibit significant decreases in strength in the z direction. This anisotropic strength is the one of the main reasons that parts are oriented in ways that require significant support structures. Because of the larger strength requirements of LFAM parts, it is even more important to consider the print orientation, support requirements, and direction of forces in your parts during the design phase and before printing.

Minimize supports and overhangs

Because of the large volume of material, and the lack of secondary extruder on current LFAM systems, support structures are very difficult to remove. The materials are stronger and better connected than in FFF printing, and so require cutting or significant post processing to remove. Overhangs are also a common difficulty, because the large mass of bead on a LFAM print is more likely to become detached and fail the print. Careful part design and thorough testing of your printer is advised to combat these issues.

Common difficulties

Difficulties over small scale

Warping

LFAM prints tend to exhibit a significant amount of internal stress due to the higher temperatures, larger size, larger bead width, and height. LFAM parts which have not been designed to minimize warping, or parts that use unmodified 3d printing thermoplastics, can be displaced 25mm(1in) per meter or more in the printing process. To combat this warping, choose materials with low shrinkage rates, and ones filled with short strand fiber materials such as glass and carbon.

Temperature control

In desktop scale 3d printing managing the temperature of the printed material is relatively easy. Because of the low volume of material deposited, simple cooling fans can be used to cool the deposited material quick enough to avoid slumping. This smaller thermal mass is also beneficial to inter-layer bonding because the extruded material can more easily heat the previous layers. Because of the larger scale and volume used with LFAM, it is difficult to keep the layers cool enough to avoid slumping, while keeping the previous layer hot enough to bond well with the newly deposited material.

To manage this problem, we use the concept of re-coat temperature. Re-coat temperature is the temperature range at which the new layer can adequately bond to the next layer, but can also cool quickly enough to not deform. This temperature will depend on the material being used and its additives, along with the layer height and width. One common way to manage the re-coat temperature is to either speed up, or to add pauses to allow for the previous layer to reach the desired temperature range. The part geometry plays a large role in the re-coat temperature. The larger the layer the more time will pass between when the extruder puts down a layer and when it comes by the same spot to recoat on the next layer. Parts with really long layer times may have to be printed at higher temperatures to keep the re-coat temp in the acceptable range. The re-coat temperature is usually just below the glass transition temperature of the material, and suppliers who are experienced in LFAM can usually provide that number for you.

Layer adhesion/delamination

Interlayer adhesion is the strength of the bond between the layers of the print. The key factors that contribute to interlayer adhesion are material properties, re-coat temperature, warping forces, and any sort of compacting or rolling of the layer after extrusion. Because of the increased warping forces in large format prints, they tend to delaminate as they are cooling. This can even happen after the print has completed. One way to mitigate delamination is to design your part so that you don’t have long runs, or thin wall sections, which will align all the force in one direction as the part shrinks and cools. It is vitally important to ensure that the re-coat temperature is within the ideal range so that you get good bonds between the layers instead of cold joints, which are much weaker. Another way to deal with delamination and weak adhesion is to compact the layer after extrusion. Compaction increases surface area between the layers and ensures good contact. Some projects have even gone so far as to anneal the parts after printing to allow the internal stresses to relax. Be careful with post heat treating as it can easily deform your parts in unexpected ways if not tightly controlled.

Oozing/Stops and starts

A common problem with the large format screw extruders is that as they process the material, they build up pressure and can continue to extrude material for some time, even after the drive motor has stopped. Most new extruder systems have built in features such as stop valves or pressure relief to combat this problem. Another way to deal with oozing is in the tool path software. You can instruct the extruder to turn off a set time before it reaches the end of the bead, so that extrusion stops at the correct point. Compaction strategies can also mitigate this problem slightly, as they ensure that even if the layer is over extruded, it will not leave material above the layer, which could cause the extruder to crash as it prints the next layer.

Poorly dried material

Poorly dried material is a major cause of headaches which is easily avoidable with proper equipment and procedures. Using a properly design pellet drying system and ensuring that the material has had enough time to dry before printing, can eliminate this problem. Hygroscopic (moisture absorbent) materials such as ABS and Nylon will extrude extremely poorly when not dried to specifications. The excess moisture can cause discoloration, poor surface finish, and decreased mechanical properties. If you notice that your print is showing excess oozing, bubbling, or is producing visible water vapor at the extruder nozzle then you should check your material to ensure it’s properly dried. Other materials may not show the effects of excess moisture as readily and you may end up with increased delamination and brittleness after printing.

Software and equipment

Software

Just like in desktop printing you will need to turn your parts geometry into commands which the printer can run. To accomplish this, you will need to use three types of software. A slicer for turning the part geometry into a toolpath. Simulation software for checking that the toolpath can be executed safely and accurately, and to analyze the effects of heating and warping. And lastly machine control software. these programs may be combined into a single piece of software, or each be done separately depending on the workflow you choose. The workflow that is included in this presentation uses Fusion 360 to slice the part and simulate the tool path. Fusion 360 is also used to generate the robot code which could be used to drive the robot. We use ABB robot studio for safety simulation to ensure the robot is doing what we want it to and interface with the actual robot controller.

Slicing/Tool path generation

The first step is to create a toolpath that follows the geometry of your part. This step is similar to desktop FFF but there are a few exceptions I will discuss. Because of the large volume of material and nozzle sizes, it is ideal to run the part with as few starts and stops as possible. The ideal toolpath has a single start and stop for each layer and runs as one continuous line. This is not always possible, but at a minimum ensure that the infill is linked into one continuous path.

Simulation

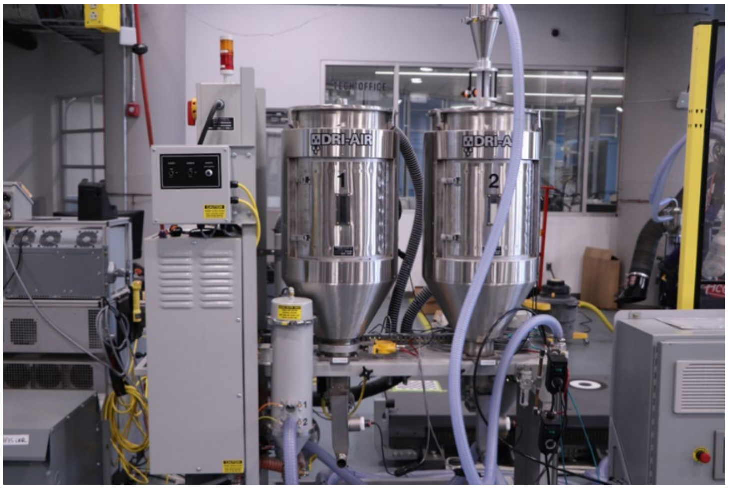
There are two types of simulation which can be performed, machine simulation and process simulation. Machine simulation mimics the movements of the extruder/robot to check for crashes and singularities. Process simulation uses material deposition, heat input, and cooling rates to give you an estimate of how the final part will turn out. It predicts whether the part will distort or warp. Process simulation is not yet widely available, but can greatly improve the quality of parts made with this process. At a minimum, simulating the robot or motion system is required to ensure the safe operation for both equipment and personnel.

Robot/Machine control

Depending on the brand of robot, you may need specialized software to interact with the robot controller, and to make changes to the robot code on the fly. This software is provided by the manufacturer and usually includes safety certified robot simulation so that you can test your robot code virtually before running the actual machines. On fully integrated gantry systems like the LSAM or BAAM there is a control panel running specialized software to control machine parameters and start and stop the equipment.

Equipment

To get started printing large parts like this there are generally two routes to take. Purchasing a fully integrated system that is matched to the specifications of the parts you are thinking of making. Or designing and integrating your own system. Building your own system will allow you to reuse equipment you may already have. Obviously one of the benefits of purchasing a much more expensive but fully integrated system is the support and ease of use you get. Things like calibrating flow rates and integrating extruder I/Os, which are required when building your own system, can be difficult for people who do not have previous robot or LFAM experience. The LFAM Process is rapidly maturing rapidly and all those challenges are getting easier every day.



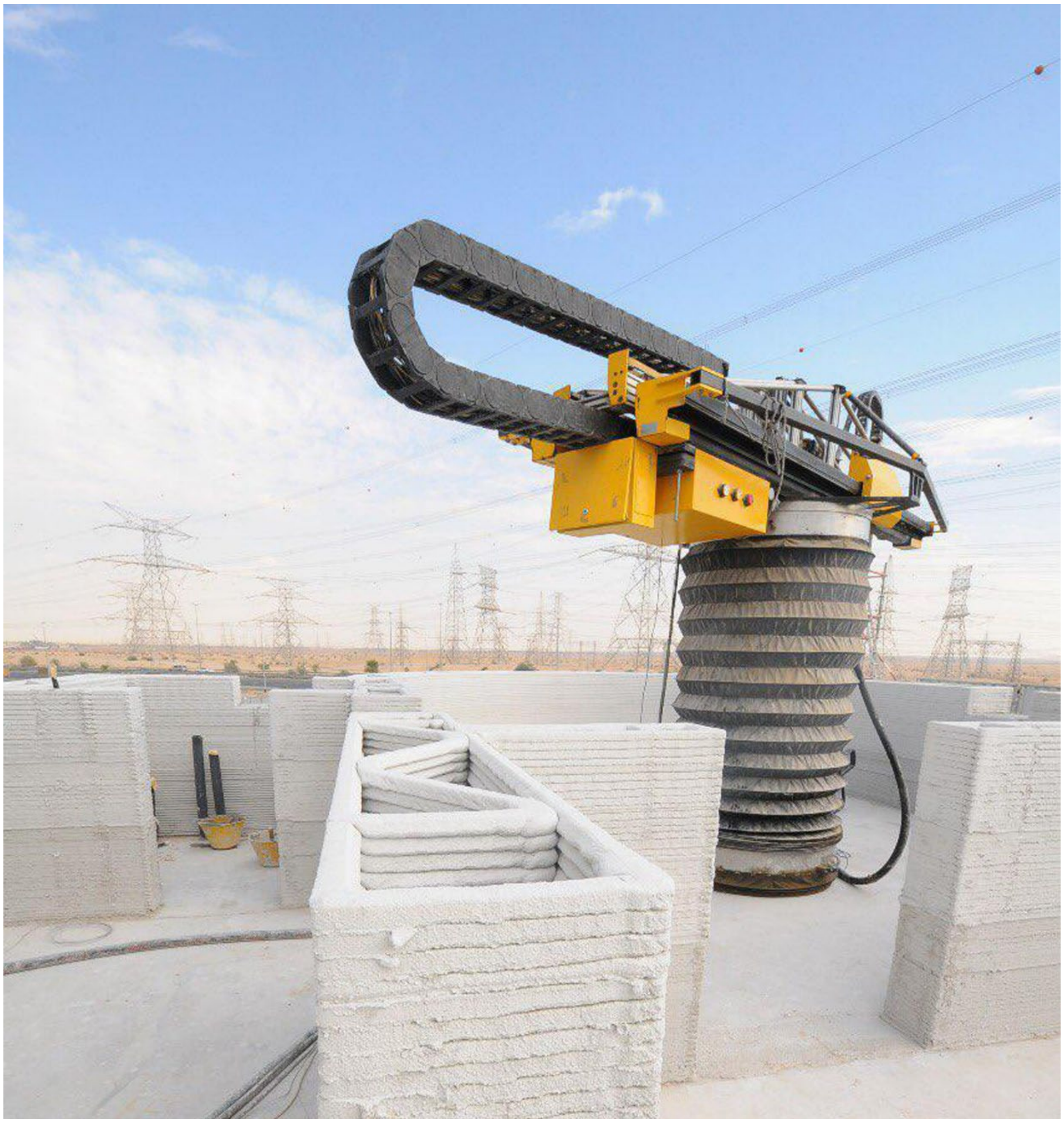
A Dry-Air pellet drying and feeding system

Pellet drying

As discussed above having a properly dried feed stock is vital when using Hygroscopic materials like Nylon, ABS, PET, and PC. You should select your pellet drying system based on the through put of your extruder so you can be sure you are drying material fast enough to keep up with you printing process. These machines are usually sourced directly from the injection molding industry.

Pellet feeding

The pellet feed systems are usually integrated with the drying systems and are generally sold as a single package. Before looking to purchase a system, you want to have an idea of your shop layout and the run length of your feeding hoses. It is common to run these systems along the ceiling and drop down into the motion system. You also want to ensure you have enough slack in the system to accommodate moving through the entire build volume. For experimental testing a refillable hopper can be used on top of the extruder, but the stops and starts associated with filling it will cause problems with the layer temperature of large parts.



Apis Cor motion system for concrete extrusion https://www.apis-cor.com/

Robot/Motion system

You need to be able to move the extruder though space and there are two common ways to do this. Industrial robot arms and gantry systems. There are other motion systems like the Apis Cor concrete printer shown above, but they are less common. In very general terms 6-axis industrial robot arms are more flexible in the tool paths they can use and can be reconfigured with an endless number of accessories. Gantry style systems tend to be more rigid and have a greater reach, but can take significant infrastructure to install.

Extruder

The heart of the LFAM system is the extruder. When deciding what extruder to use you should consider a few different factors. You should have already determined the size of the largest parts you are planning to print and have a general idea of the smallest feature resolution you need. These two things will help you determine your maximum flow rate and nozzle sizes. Having an extruder with a wide temperature range can be very useful if later you decide to change material specifications and move to higher performance polymers, which usually require higher printing temperatures.

Process related specifications

- Maximum temperature: This will determine which materials you can run.
- Max flow rate: the maximum amount of material the extruder can process per hour. This will dictate your print speed.
- Available nozzle sizes: Nozzle size is directly related to resolution and bead dimensions and by association print speed. Smaller nozzles will give you better resolution and smaller feature sizes at the cost of big reductions in print speed and increases in print time.

Extruder features

- Dynamic flow rate control allows you to change the extruder flow rate as the motion systems speeds up and slows down for corners and changes in direction. This allows for more consistent beads and better performance.
- Anti-ooze: needed to control built up pressure in the extruder tube and prevent material from leaking out after the extruder has stopped. Can be accounted for in tool path programing.
- Melt sensor or nozzle temp sensor: It is important to know the actual temp of material exiting the nozzle.
- Tamping, rolling or compaction: a device for compressing the bead after extrusion to aid in adhesion between layers and provide a more consistent layer height.
- Data logging.

Print Bed

The print bed is the literal foundation of the LFAM process. Your options for print bed will largely depend on the size of the parts you are trying to make and the materials you are using. While heated beds have become the standard in desktop printing heating the platform of a 20’x8’ area can be both expensive to implement and costly in terms of energy usage.

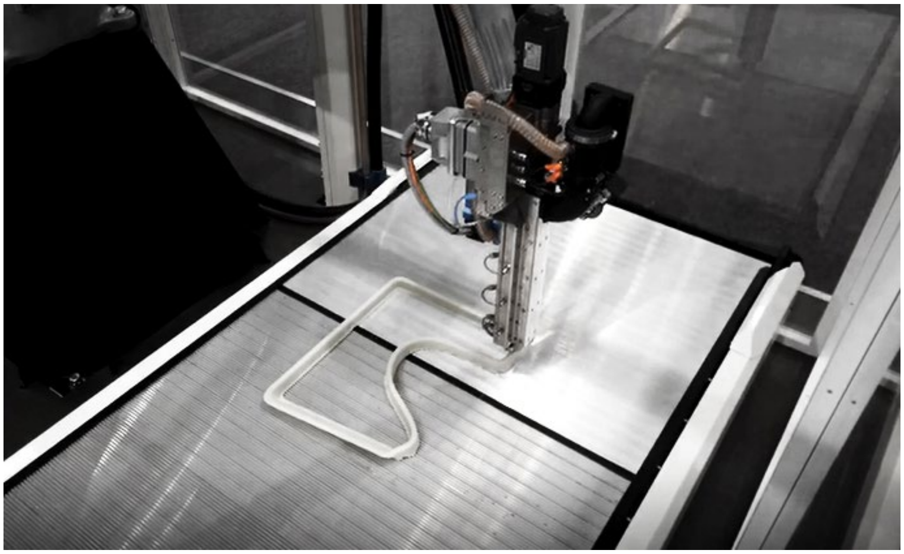
Bead board

One way to adhere the first layer is to use a surface that can grip the material as it is printed, but not so securely that the parts cannot be removed when printing is completed. One low cost method for this are called Bead boards. They are comprised of a stiff base material, usually MDF or plywood which has the feed stock pellets glued down to it in a single flat layer. Bead Boards are low cost and provide very good adhesion but cannot be easily reused and require a fair amount of work beforehand.

Bead board. Autodesk Technology Center Boston

Aluminum slats/Mechanical adhesion

Another option is the CEAD print bed which is made up of a set of closely spaced aluminum extrusions with fins that allow some printed material to flow around them. This provides good mechanical bonding by allowing the material space to fit down into while supplying a flat level area for the print. To release the part the slats are turned so that the angle is changed, and the part can be easily removed. Print beds like this offer ease of use and portability but are difficult to scale to much larger sizes.



CEAD aluminum extrusion print bed. https://cead-am.com/

Vacuum tables

Increasingly, large vacuum hold down tables are being used as print beds. Vacuum tables offer a very large printable area which is exceptionally flat and level. They increase adhesion by holding down sheet material of the same makeup as the feed stock. This allows the first layer to partially melt into the sheet and provide excellent adhesion. This also allows the use of any material which you can find in both pellets and sheet.

Heated beds/Heated chambers

Finally, we have heated beds. Printing on a heated aluminum bed can provide a high-quality platform for LFAM prints. It offers excellent stiffness, flatness, and can be very precisely leveled. A heated print bed of this size produces a large amount of escaping energy. If designed correctly the entire print volume can be kept at an elevated temperature during the print process just with the heat produced by the print bed. Bed heating can be accomplished several ways, but silicone heater pads from the composites industry have become a common choice.

Heated bed on a Cincinnati Incorporated BAAM printer. www.e-ci.com

Resources for LFAM

It would be impossible to cover all the information on such a dynamic and quickly growing process all in one document so I have included links to additional resources which I hope will help guide you on your path to successful large printing. This list is not exhaustive but will give you a good starting point for investigating the industry.

Process information

- Overhangs and self-supporting: https://www.additiveeng.com/self-supporting-angles-in-large-scale-additive-manufacturing/
- Oak Ridge National Laboratory, LFAM research: https://www.ornl.gov/facility/mdf
- Controlling substrate temperature with infrared heating to improve mechanical properties of large-scale printed parts: https://www.osti.gov/biblio/1606965-controlling-substrate-temperature-infrared-heating-improve-mechanical-properties-large-scale-printed-parts

Equipment manufacturers

- BAAM, Cincinnati Inc.: https://www.e-ci.com/baam
- CEAD, robot and gantry printers, extruders, print beds: https://cead-am.com/home/solutions/
- LSAM, Thermwood Inc.: http://www.thermwood.com/lsam_landing_page.htm
- Hybrid Manufacturing Technologies, polymer and metal extruders: http://www.hybridmanutech.com/
- Stranpresse extruders: http://strangpresse.com/

Service bureaus

- Additive Engineering Solutions:https://www.additiveeng.com, fabrication, design and engineering consulting.

General additive resources

- 3D Printing Industry
- Additive Manufacturing Magazine
- Digital Engineering
- Advanced Materials
- 3D Printing and Additive Manufacturing
- Rapid Prototyping Journal
- Journals of Materials Processing Technology

Conferences, workshops, and professional societies

- Additive Manufacturing User's Group (AMUG)
- RAPID + TCT
- formnext

Standards

- ASTM Overview of Additive Manufacturing Standards
- America Makes and ANSI Additive Manufacturing Standardization Collaborative