

Galvanometer Scanning Technology for Laser Additive Manufacturing

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ABSTRACT

A galvanometer laser beam scanning system is an essential element in many laser additive manufacturing (LAM) technologies including Stereolithography (SLA), Selective Laser Sintering (SLS) and Selective Laser Melting (SLM). Understanding the laser beam scanning techniques and recent innovations in this field will greatly benefit the 3D laser printing system integration and technology advance. One of the challenges to achieve high quality 3D printed parts is due to the non-uniform laser power density delivered on the materials caused by the acceleration and deceleration movements of the galvanometer at ends of the hatching and outlining patterns. One way to solve this problem is to modulate the laser power as the function of the scanning speed during the acceleration or deceleration periods. Another strategy is to maintain the constant scanning speed while accurately coordinating the laser on and off operation throughout the job. In this paper, we demonstrate the high speed, high accuracy and low drift digital scanning technology that incorporates both techniques to achieve uniform laser density with minimal additional process development. With the constant scanning speed method, the scanner not only delivers high quality and uniform results, but also a throughput increase of 23% on a typical LAM job, compared to that of the conventional control method that requires galvanometer acceleration and deceleration movements.

Keywords: Galvanometer, beam steering, laser additive manufacturing, LAM, Selective Laser Melting, uniform laser density, digital scanning technology, dynamic trajectory planning

1. INTRODUCTION

Laser Additive Manufacturing (LAM) refers to the process of using a laser as the heat source to produce 3D objects layer by layer. Depending on the material used and the process to produce the part, LAM technologies are categorized into three categories: Stereolithography (SLA) that uses UV laser sources to cure photo-reactive resins to make models with fine details, Selective Laser Sintering (SLS) that uses CO₂ lasers to sinter polymers to create plastic prototypes and occasionally final parts, and Selective Laser Melting (SLM) that uses fiber lasers to melt metal powders to build mostly finished functional parts.

Of these three technologies, Selective Laser Melting has shown the most rapid growth in recent years as it builds functional parts that go into automobile and aerospace^{1,2,3}. The advantages of SLM technology over conventional manufacturing methods include the following^{2,3}: it is less expensive in manufacturing large and complex parts; it is flexible and adaptive and creates less burden when building custom parts; and it allows engineering of light-weight and complicated parts without compromising performance that is difficult to achieve with traditional manufacturing method. The major challenge, however, for adopting LAM technology (SLM in particular) for mass production is still the cost per unit manufactured. As illustrated in Figure 1, while cost per unit manufactured goes down with volume for conventional manufacturing (black curve), it remains the same for additive manufacturing (blue curve) no matter how many parts are being made⁴. Two effective ways to reduce cost are to improve the part quality/yield and to improve the job throughput making each part.

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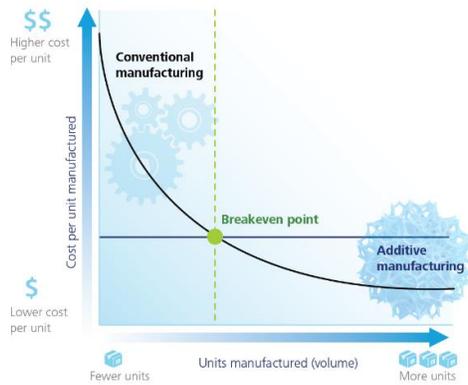


Figure 1. Cost vs volume for additive manufacturing compared with conventional manufacturing⁴

In a typical LAM machine using any of the three technologies, one of the key components that affects processing quality and throughput significantly is the galvanometer-based scanner and its scanning controller. Therefore, understanding the galvanometer based scanning technology and recent innovations in this field will greatly benefit the Laser Additive Manufacturing technology development and its applications. How accurately the scanner steers the laser beam to the target location of the working surface determines the part geometric precision. A high quality part also requires that the uniform laser density is delivered at the materials⁵. The conventional method to control the scanner movement typically involves acceleration and deceleration at ends of the hatching and outlining patterns. This can lead to non-uniform laser power density on the material affecting the melting or sintering characteristics. So a different scanning control strategy is needed. In this paper, we demonstrate two control techniques to deliver uniform laser density on the material to be processed. The ability to deliver uniform laser density will greatly improve the quality of the part built.

There are several techniques to improve the LAM process job throughput. One seemingly obvious method is to increase the processing speed when the scanner steers the laser beam on the material. This method requires higher laser power to ensure enough laser energy interacting with the material in a given amount of time. In Selective Laser Melting, up to 1kW fiber laser power has been adopted^{3,6}. However, the max processing speed obtained today is mostly limited by the laser-material interaction, not by the maximum scanning speed of the scanner. The typical processing speed is ~3m/s at 450mm working distance. Having said that, a high speed scanner can still increase the job throughput because it allows faster jumps between the locations when laser is off. Another commonly used and effective strategy to improve throughput is parallelization, i.e. using multiple scan heads in one LAM machine – these scan heads can either perform same jobs, or process different jobs for different parts, or process different areas of the same part.

One of the smart control techniques that we are going to present in this paper is shown to achieve 20-30% improvement in overall job throughput for typical LAM jobs in addition to delivering uniform laser density. The throughput improvement is accomplished by not limiting the jump speed in the scanner control therefore fully utilizing the dynamic capability of the high speed digital scanner, and also by optimizing the job trajectory in coordination of the scanner motion planning.

2. DIGITAL SCAN HEAD TECHNOLOGY FOR LASER ADDITIVE MANUFACTURING

An LAM machine based on galvanometer scanning requires fast scanning speed for higher throughput, high scanning precision and stability for high fidelity of the part built. To meet the application requirements, the design of the galvanometer scanning system focuses on reducing inertia of the moving components including mirrors, increasing the motor-servo driving power and efficiency, and increasing position control accuracy over time and over environment conditions. For an LAM machine with a large build area, a 3-axis scan head with dynamic Z-axis for field flattening is commonly employed.

Beryllium is typically used to fabricate high performance scanner mirrors. It has the lowest material density of 1.85 g/cm³ and the highest specific stiffness of 160x10⁶ m²/s² compared to other mirror materials including Silicon Carbide,

Fused Silica and Silicon. In addition, its high manufacturability enables complex geometric structure design achievable with conventional machining technologies. The back of the mirrors are often designed with structure to reduce as much material as possible while maintaining the flatness of the mirror under high speed rotational movements. To improve the motor-servo driving efficiency, pulse width modulation design can be employed. A commercially available digital scan head with 30 mm mirrors aperture with those design elements can routinely work at 50 rad-optical/s scanning speed.

Being able to detect the mirror position with high accuracy and provide effective position control is key to the scanning precision. High position accuracy has been demonstrated with a 24-bit position encoder, 24-bit command position resolution and predictive state-space servo control with our Lightning™ II digital scan head. For example, in a 400mm x 400mm field with a working distance of 450mm, the smallest step one can command is 17 nm with 24-bit resolution compared to only 4.5 μm with 16-bit command resolution. This ultra-fine command resolution together with the repeatability of 2μrad allows the LAM machine to achieve <10μm patterning accuracy in a 400mm x 400mm work field with the digital scan head.

Low long-term drift and thermal stability is essential to LAM process that can take hours or days to build the part. The low drift digital position encoder and adaptive thermal model used in servo control can effectively reduce the drift induced by temperature change and over time. Water-cooling of the galvanometer can also be used to keep motor running at a constant temperature to further reduce the drift.

3. SMART CONTROL TECHNIQUES FOR UNIFORM LASER DENSITY

Although digital scan head technologies discussed above can enable fast, accurate and reliable pattern definition in Laser Additive Manufacturing, digital galvanometer scanners, being a physical system, still need to accelerate and decelerate whenever its motion is changed. With conventional control methods, each commanded vector is constructed such that the scanner starts its motion from being static and finishes the vector returning to zero velocity. So there's always acceleration and deceleration periods in which scanner moves at slower speed than the intended one. Often the laser power is kept constant, so this results in more laser energy deposition per unit area in these phases. This non-uniform laser energy deposition in the additive manufacturing process impacts the local material melting characteristics and creates inhomogeneous material property such as stain or stress in the finished parts. Such finished parts may cause defects or latent failures in functional devices for space craft or automobile vehicles. Therefore uniform laser density is critical for LAM processes, especially for SLM.

In this section, we will discuss two methods to maintain uniform laser density: one is to keep the scanner velocity constant during lasing period; the other one is to modulate the laser based on the variation of the scanner velocity. Both methods have been implemented in ScanMaster Controller.

3.1 ScanPack for constant velocity control

ScanPack control scheme is an adaptive scan control based on advanced servo model. It uses the accurately predicted galvanometer position information provided by the servo model and dynamically adapts the scanner and laser commands to the current conditions and job requirements. In short, ScanPack control algorithm plans the scanning trajectory automatically and coordinates laser firing based on the scanner's dynamic characteristics as well as the job accuracy requirements. The job requirements here not only refer to the accuracy requirements on pattern shape fidelity such as corner sharpness, but also include process requirements, for example the required velocity at both ends of a vector, for the reason that the scanning velocity affects the laser energy deposition and hence affects the processing quality.

Figure 2 illustrates basic differences between conventional control scheme and ScanPack control scheme. With conventional control scheme, the commanded trajectories are irrespective of the scanner capabilities, and the scanner always stops at the vector ends for either mark or jump vectors. In contrast, with ScanPack control, the desired velocity at the ends of mark vectors (end velocity) can be set based on the process needs. The requirement of the corner sharpness can also be specified. During marking when the laser is on, ScanPack commands the scanner to strictly follow these requirements. During jumping when the laser is off and scanner acceleration/deceleration does not affect processing, ScanPack plans the jump trajectory to meet the marking requirements with minimal time, while making sure that performing such a jump is still within the scanner's dynamic capability so the scanner never goes unstable or unpredicted.

In the examples shown in Figure 2, for ScanPack to mark line A-B and line C-D in the top of the figure, the scanner will transverse both lines with the set mark speed and the end velocity. When jumping from B to C, jump trajectory is planned. If the end velocity is set small, the jump needs shorter turns and shorter path, shown in red curve; if the end velocity is set larger, with the same scanner, it will needs longer path to make the turn, shown in blue curve. For ScanPack to mark corner A-B-C, depending on corner sharpness requirement, speed at the corner and how fast the scanner can move, ScanPack determines if the scanner should go round the corner, or it needs to leave the corner, jump a ‘skywriting’ loop and then enter the corner with the same speed. When ‘skywriting’ loop is triggered, the marked corner is always sharp. These two examples represent marking ‘hatching’ and ‘outlining’ of a typical LAM pattern. In LAM, the end velocity can be set the same as the process velocity to maintain uniform laser deposition throughout the entire job.

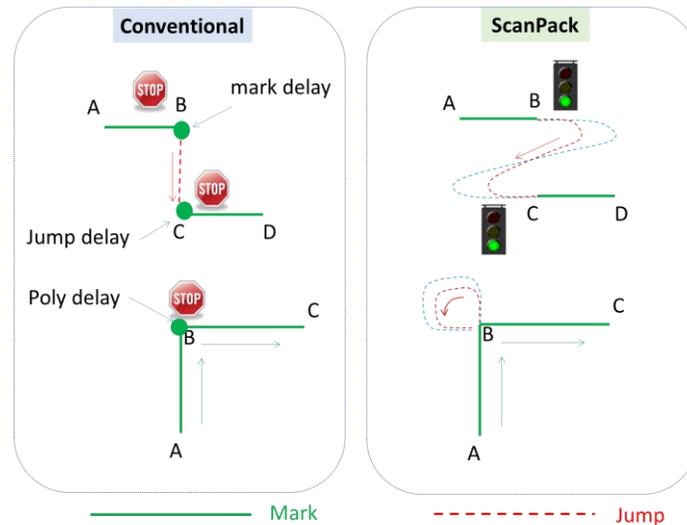


Figure 2. ScanPack trajectory planning compared to conventional control commands

We performed the following marking experiment to demonstrate uniform laser density with ScanPack control and compared it with the conventional control scheme. A Lightning II digital 3-axis scan head with 30mm mirror aperture is controlled by a ScanMaster Controller which supports both conventional control and ScanPack control algorithm. ScanMaster Designer software is used to import a 3D model (.STL, .STEP format and etc.), slice it into layers and create hatching pattern for each layer. To illustrate the processing result, an IPG YLP 20W pulsed fiber laser is used to mark on an aluminum coated glass substrate.

To make the experiment more general and less subjective, a 3D model of ‘Thin Wall Test’ from a 3D model open-source website (<http://www.thingiverse.com/>) is selected⁷. The working field was set to be 300mm x 300mm with a working distance of 370mm. The marking speed is chosen to be 2.7m/s in the typical range used in SLM process. We first imported the thin wall structure 3D model into the ScanMaster Designer software, sliced the 3D model into layers, and converted pattern in each layer into outlines and hatching patterns as shown in Figure 3. One layer from the layer stack is used to perform the marking experiment.

When marking this layer with conventional control, all delay settings are manually optimized to obtain accurate pattern definition. When marking this layer with ScanPack, delay values do not need to be specified. Instead, the corner sharpness with the max radial error is defined to be 100μm, and the end speed is specified to be the same as the mark speed (End Velocity Ratio = 100%). The max radial error refers to the distance from the rounded corner tip to the ideal sharp corner tip, as shown in Figure 4. Note that we deliberately laser marked the outlines and the hatching pattern of this layer separately in order to better demonstrate the difference.

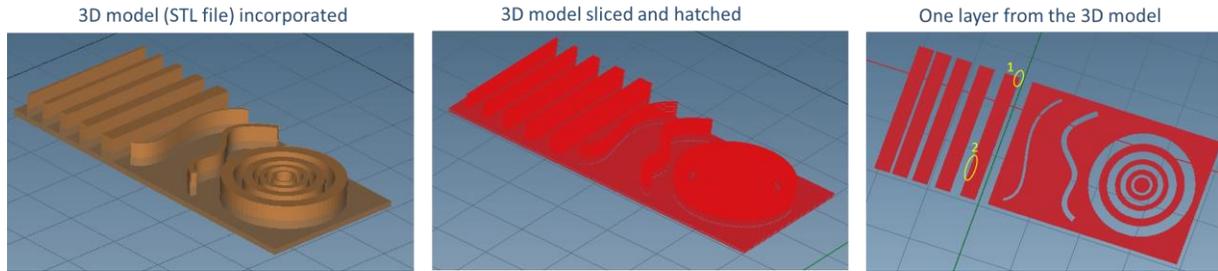


Figure 3. The ‘Thin Wall Test’ 3D model is imported into ScanMaster Designer (left), sliced into 10 layers with hatching created (middle) and one layer (right) is selected from the layer stack for this marking experiment. Note that location 1 highlights the corner in the outline and location 2 highlights the hatching pattern where the marking results are shown in Figure 5.

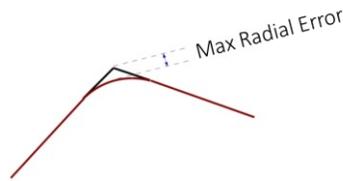


Figure 4. Max Radial Error is defined as the ‘tip’ of the actual marked corner to the tip of defined corner

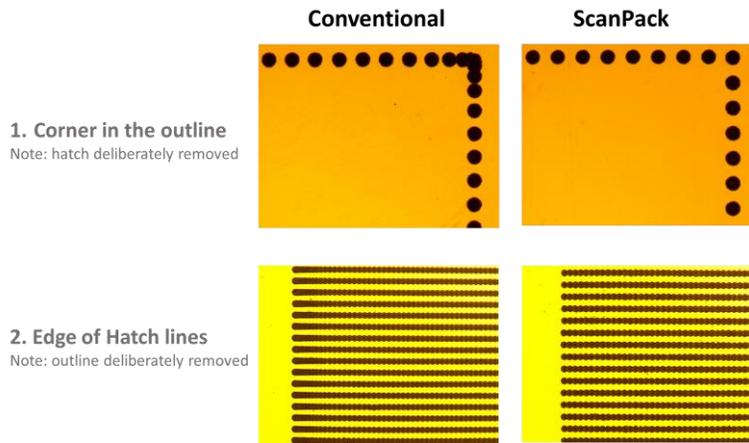


Figure 5. Marking results with conventional and ScanPack control. The comparison is focused on a corner in the outline pattern (top) and the edge of hatch lines (bottom).

Marking results with conventional and ScanPack control are compared in Figure 5. The top group are pictures of the marked corner at location 1 in Figure 3 by conventional and ScanPack control, respectively. The laser modulation frequency was set such that laser spots were separated at this marking speed to show the difference. It is clear that with conventional control the laser spots are more densely packed at the corner, while with ScanPack the laser spot density throughout the corner is uniform. The absolutely sharp corner with ScanPack suggests that the Skywriting jump loop was triggered in order to complete the corner with constant velocity while meeting the corner accuracy requirement. The bottom group are pictures at the ends of hatch lines at location 2 in Figure 3. The laser modulation frequency was again set to separate laser dots but at higher frequency than that used in outline so that it is easy to show the individual hatching lines. With conventional control, the laser dots are more densely deposited close to the edge of the lines; while with ScanPack, the laser deposition is uniform throughout the entire line.

This marking experiment demonstrated constant velocity therefore delivering uniform laser density in processing both outlines and hatching parts in laser additive manufacturing jobs using ScanPack control with a digital scan head.

3.2 Velocity Based Laser Modulation

The other control method to achieve uniform laser density is to modulate laser based on scanner speed change. Modulation can be done on laser frequency, laser power or laser pulse width. At the ends of vectors when the scanner accelerates or decelerates, the laser frequency or power or pulse-width will be modulated accordingly to compensate for slower scanning speed. Figure 6 shows an example of laser frequency modulation as a function of scanning speed. Velocity Based Laser Modulation can be used either in conventional or ScanPack control, although it's often more applicable in conventional control scheme.

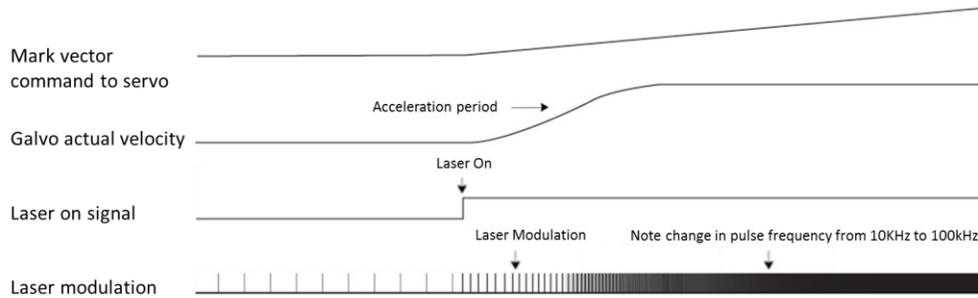


Figure 6. Velocity Based Laser Modulation on frequency. When the mark vector command (1st curve) starts and the laser is turned on (3rd curve), the galvo velocity (2nd curve) increases from zero and gradually to a constant value, and the laser modulation signal (the bottom curve) increases from 10kHz to 100kHz accordingly.

For ScanMaster Controller to coordinate the laser modulation with respect to the scanner's speed, two variables can be adjusted to achieve optimal condition. One variable is the scanner's bandwidth to simulate the actual acceleration or deceleration behavior. The other is laser modulation range. For example, laser power can be varied from a minimum non-zero value to the nominal value when the velocity changes from zero to the mark speed. In Figure 6, the laser modulation frequency is set from 10kHz to 100kHz. Finding the optimum values of bandwidth and modulation range is usually a trial and error process.

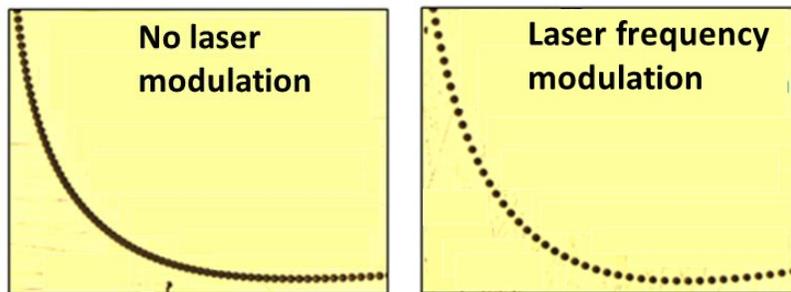


Figure 7. Marking results of a corner with conventional control with no laser modulation (left) and with velocity-based laser modulation on frequency (right). Velocity-based laser modulation clearly improves the uniformity of laser density at the corner.

Figure 7 shows the marking results of a corner with no laser modulation (left) and with velocity-based laser modulation (right). The laser power is kept constant and laser frequency is modulated. Using velocity based laser modulation to compensate for scanner deceleration and acceleration at the corner indeed shows much more uniform laser pulse density throughout the corner.

4. SCANPACK CONTROL ALGORITHM IMPROVES LAM THROUGHPUT

Unlike ScanPack which optimizes scanning trajectory for accuracy, conventional control relies on time delays after scanner motions to achieve desired accuracy. These time delays are usually the same for entire job, and are set to accommodate the most demanding part of the job resulting in unnecessary processing time increase. Also finding the right set of delay values is a trial-and-error manual exercise adding to job set-up time. With ScanPack, no delay settings are needed and jump trajectory planning is automatic. Only accuracy and speed requirements which are usually straightforward are required when setting up a new job. So job creation is much easier and quicker with ScanPack.

In conventional control, user needs to define jump speed connecting each mark vectors; while ScanPack does not limit jump speed. The scanner is allowed to jump at its maximum acceleration. This unique advantage in ScanPack contributes to throughput improvement in LAM jobs. Furthermore, by adopting adaptive and local trajectory planning, ScanPack can optimize the scanner movement based on the regional pattern accuracy and speed requirements, often resulting in improved overall job throughput compared to conventional control scheme.

Using the same thin wall structure 3D model and the previous experimental set up, we compared the job throughputs between the conventional and ScanPack controls. This time we ran the entire layer stack of the 3D model (as shown in the middle picture of Figure 3). Table 1 lists the detailed processing parameters used in conventional and ScanPack controls, respectively. The delay settings used in conventional control is optimized to achieve similar pattern quality as ScanPack. Note that when we ran this laser additive job with the two control schemes, we did not wait for the additional time between layers for material feeding. We simply let the scan head to mark 10 layers continuously.

The overall job throughput with ScanPack control is 30.4s. Compared to the processing time of 37.4s with conventional control, the job throughput is improved by 23%!

Table 1. Thin Wall Structure LAM job parameters and throughput comparison

Thin Wall Structure Job Parameters			
Conventional		ScanPack	
Mark Speed	2700mm/s	Mark Speed	2700mm/s
Jump Speed	2700mm/s	Jump Speed	n/a
Mark Delay	300μs	Mark Delay	n/a
Jump Delay	150μs	Jump Delay	n/a
Poly Delay	75μs	Poly Delay	n/a
Job Throughput	37.4s	Job Throughput	30.4s

5. CONCLUSION

This paper presents the latest digital scan head technologies and control algorithms for the laser additive manufacturing process.

The 24-bit high resolution digital position encoder enables precision pattern definition even in large work field usually required by LAM. Although current marking speed used in LAM is limited by laser material interaction, the fast speed and highly dynamic performance of digital scan head allows fast jumps between patterns and shorter delays to transition between patterns, therefore fast scan head can still greatly improve the throughput. Furthermore, low drift galvo and

highly efficient servo with adaptive thermal model are key for stable long time operation typically required for LAM jobs.

Building high quality functional parts with LAM also requires that the scan head delivers uniform laser density on the material. To accomplish that, we have implemented two control strategies in ScanMaster Controller. One is to maintain constant velocity with ScanPack control algorithm, and the other one is to modulate laser to compensate for any velocity variation. Both methods have been demonstrated in experiments to deliver uniform laser density in typical LAM jobs.

ScanPack, different from conventional control scheme, is an accuracy-oriented job optimization algorithm. It not only allows end velocity control for achieving constant velocity, but also eliminates delay settings as well as the limit on jump speeds. This greatly reduces job set-up time and improves the overall job throughput. Our experiment demonstrated that ScanPack can improve overall throughput of a typical LAM job over conventional control by 23%.

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