Lasers in Manufacturing Conference 2019

Using wobble based laser scanning techniques in additive manufacturing applications

Simon Matthias[a], Mark Lucas[b], Seetharam Sivam[b], Bhavesh Bhut[b*]

aNovanta Europe GmbH, Parkring 57-59, 85748 Garching bei Munchen, Germany
bNovanta , 125 Middlesex Turnpike, Bedford, MA 01730, United States America

Abstract

In metal powder bed based additive manufacturing, much focus is placed on relatively abstract scanning trajectories and techniques. While this is a fundamental and complex part of the process that necessitates such focus, scanning technology has a part to play in productivity and part quality. Often machine manufacturers and end users need to add additional parametric information into their trajectory planning obscuring the underlying technology. This detail is hard won and understandably often leads to a closed manufacturer specific file formats containing the meta data required to operate the machine. This article describes wobble based scanning techniques that may be employed to deliver enhanced part quality and productivity

Keywords: Additve Manufacturing ; Laser Powder Bed Fusion;Laser Scanning;

1. Introduction

Productivity of laser based powder bed additive manufacturing machines is subject to much attention at the present time. Numerous strategies are being pursued within the industry to deliver enhanced productivity. These include multiple scanning heads, various scan field overlap strategies and more recently research undertaken by Tsai et al [1] explores the possibility of using multiple spot scanning strategies. Many more novel methods and approaches are being worked on. As the industry continues to transition from prototyping

* Corresponding author. Simon Matthias Tel.: +44-747-103-7239
E-mail address: simon.matthias@novanta.com

to series production of functional parts, productivity is key to making the part economically. This paper explores one possible approach to improve productivity.

2. Literature review

A cursory review of literature yields many papers describing scan trajectory patterns. While this paper will summarize a common approach, it does not analyze such patterns in detail. Most scanning techniques used today by additive manufacturing machine builders are written with a level of abstraction. This often doesn't allow full utilization of the scanning technology. This limits the designer's ability to influence the melt pool and thus the microstructure. Consider the following points:

- Thermal Gradients. In Laser Powder Bed Fusion machines the material is exposed to a temperature gradient of 5-20K/um and cooling rates of 1-40K/um [2,3]. As the material transitions between states, Powder to Liquid to Solid. The cooling rate plays a significant part in the microstructure development and end part quality.

- Scanning Parameters. In [4-6] the influence of various scanning related parameters on the mechanical properties of SLM parts are studied. Key findings from this study demonstrate that laser power and scanning speed play a key part in the formation of the microstructure. Scan speed and laser power, directly influence whether the surface tension of the melt pool is broken, splatter ejected or powder not fully melted. All of which affects the end part quality, and can contaminate the layer.

- Melt Pool. Lawrence Livermore National Laboratory (LLNL) [8,9] use high speed cameras (500K frames / sec) and advanced computing platforms to model melt pool dynamics. Their approach has been to develop a model at the particle level, and verify with experiments using high speed cameras. In these experiments a number of observations have been published in literature including the sensitivity of the melt pool to gas flow and how scan speed and laser power contributes to the formation of the key hole, ejection of material (splatter) and pore defects.

The melt pool represents such a highly dynamic and sensitive environment, it can be difficult to conceptualize how it may be controlled based entirely on feedback (closed loop control). The argument often sited is that once the state of the melt pool is detected, measured and processed to a simple control signal, the data is already historical thus you are unable to influence. Instead quality based techniques proliferate. Machine developers often develop their own proprietary solutions incorporating a mix of on axis and off axis sensors to acquire data. Use of machine learning and statistical techniques is then used to derive useful metrics.

As real time control is so problematic, then predictive assessment and path planning becomes more interesting. To address this desire there is a burgeoning industry in simulation tools. Based on finite element models and techniques, the aim is to calculate for each layer, the best process parameters and optimized scanning patterns compensating for machine artifacts, the heat model, neighboring layers, shrinkage and many other parameters.

When considering scanning patterns and how they may influence the melt pool, a review of welding is essential. Wobble heads have been used in welding for many years, and found to have real influence on the

microstructure [7]. Typical patterns include circle, linear, figure of eight and infinity patterns, operating at frequencies typically in the range 300Hz to 1KHz. Research has found, enhanced weld quality can be attained through better control of thermal gradients. This results in a reduction in cracking and porosity. When considering additive manufacturing, the comparison to a welding process, over simplifies the process, but offers techniques that can be beneficial.

Based on the points highlighted above it is evident that there remains a place for more advanced scanning techniques that may influence the melt pool and part quality. The remainder of this paper, focuses on scanning trajectories that may be used in Laser Powder Bed Fusion (LPBF) machines to attain better material properties and improved productivity.

3. Traditional scanning patterns

Literature [4,5] discusses a number of common scanning strategies including chequerboard, linear, rotational hatching strategies. Figure 1 introduces a range of typical scanning approaches. Often the scanning strategy is still based on vector based techniques. Hatch spacing, laser spot size, scanning speed and laser power are key components that all contribute to the energy density experienced by the part, as described in [10] is defined by :-

$$\mathrm{Ed} = \frac{P}{Vht} \tag{1}$$

Where Ed represents Energy Density in J/mm^3 , P represents Laser Power in Watts, V is the Scan Speed in mm/sec, h is hatch spacing in mm and t is layer thickness in um

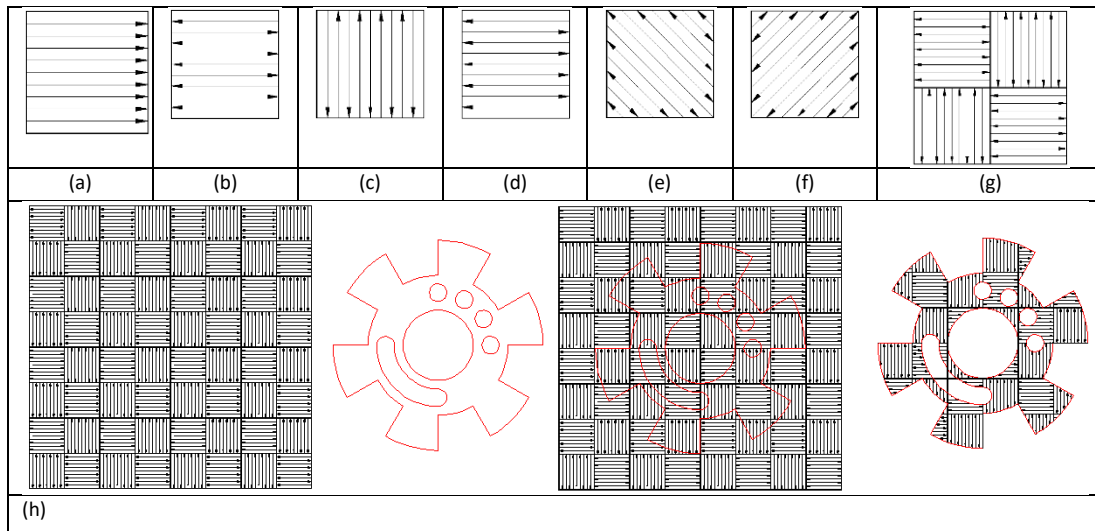| (a) | (b) | (c) | (d) | (e) | (f) | (g) |

(h)

Figure 1 – Common scanning hatch styles (a) unidirectional hatch with boundary;(b)bi-directional hatch with boundary;(c-f)Evolution of hatch orientation (rotation) layer by layer;(g)chequerboard pattern;(h)application of chequerboard pattern to part geometry

The scanning patterns described in figure 1 are defined in terms of Cartesian coordinates. In addition to this basic information the scan job designer will also add metadata such as laser on/off delay, mark/jump delays

to compensate for the dynamics of the beam steering system and to synchronize laser timing with the motion of the Galvo. Given an area that needs to be filled, the choices are often limited to unidirectional and bidirectional hatching strategies (figure 1a and 1b). The orientation of the hatch can be changed between layers as demonstrated in figures 1c to 1f. Modifying the direction of the hatch helps to build a part with better thermal history and mechanical properties. Hatch strategies can be combined on the same layer, and even within the same fill as shown in figure 1g. When applied to a layer the machine developer will take their overall scanning strategy and apply it to the required part geometry. In figure 1h, this process is represented pictorially. This approach can change the dynamic content of the scanning required. For instance, as vectors become constrained by the part boundary, the number of short vectors increases. In terms of productivity these short vectors mean that the frequency of galvo repositioning cycles (i.e. jumps) increases.

4. Wobble Based Scanning

Novanta has developed additional scanning techniques based on wobble. These modes can be defined as traditional (Modes 1 & 2) and advanced modes of operation (Mode 3). Advanced options empower the scan job architect to develop almost unlimited scanning patterns and shapes. Modes 1 and 2 are based on a repetitive pure circular geometry and maintain the vectors linear speed, whereas mode 3 utilizes a lissajous algorithm. Each of these modes are described in the following text.

4.1. Mode 1 Constant Linear mark Speed with specified period

Constant linear mark speed is defined with a constant period. In this case the wobble is defined in terms of period (in micro seconds) and amplitude in job units.
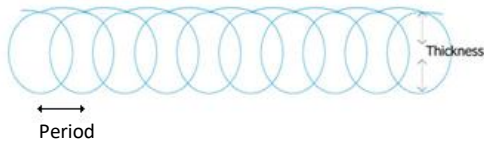
Figure 2- Mode 1 wobble definition

4.2. Mode 2 Constant linear mark speed with a specified overlap

Similar to Mode 1, in this mode the wobble characteristic is defined in terms of overlap (in percent) and amplitude in job units. For example a job geometry in units of mm will have overlap defined in mm. The shape of the wobble will always be based on a pure circle, and constrained by the bandwidth of the scanning system in use.

Figure 3 - Mode 2 wobble definition

4.3. Mode 3 – Equation based wobble (Lissajous Based Wobble)

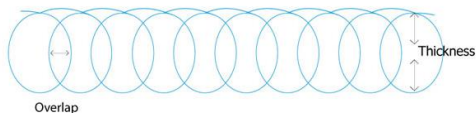In this mode wobble declarations are replaced with a more descriptive equation based declaration. The wobble motion is defined by the equations given below.

$$\mathrm{Gx}(t) = A \sin(\omega t + \phi) \quad \text{X Axis Galvo position} \tag{2}$$

$$\mathrm{Gy}(t) = B \sin(\omega t) \quad \text{Y Axis Galvo position} \tag{3}$$

Where A is X Galvo wobble amplitude in job units (often mm) , B is Y Galvo wobble amplitude in job units (often mm) , ω is the frequency in KHz converted to radians/sec i.e. $2\pi f$ (0.1 to 10KHz) , *t* is the instantaneous time in which the evaluation is made and ϕ is the phase relationship in degrees of the X axis with respect to the Y axis at the start of the waveform generation. (-180 to +180 Degrees)

Using this wobble mode allows the user to define a wobble pattern based on the Lissajous equations given in equations 2 and 3. These curves allow the developer to explore new methods of influencing melt pool dynamics, not easily readily achievable using traditional vector based job description notations.

The implementation of Lissajous wobble also introduces the concept of directionality. It is known from welding that maintaining the direction of the wobble pattern provides a better quality, more uniform end result. It is thought this benefit can also be applied to additive manufacturing.

5. Study Details

Within Novanta's application labs, tests were undertaken to explore the capability and benefits of the Wobble Modes described. The objective, to establish how more advanced wobbling techniques such as Lissajous wobble could offer unique processing and productivity possibilities in terms of energy density and scan time.

The test configuration consisted of a Fibre Laser (IPG YLP 20W), a two axis high performance scan head (Cambridge Technology Lightning II 20mm) and Wavelength Technology F Theta Lens. The system was configured with to a working area of 70x70mm and a spot size of approximately 20um. This is much smaller than that usually used in a commercial additive manufacturing machines. The intent was to obtain a clear visualization of the scanner influence on the commanded trajectory, given the equipment available. The scanner was controlled from a scanner card (Cambridge Technology ScanMaster Controller) connected to a computer.

To explore wobble capabilities using ScanMaster Controller and a High Performance Scanner, first standard wobble features with constant linear mark speed were tested (Modes 1 & 2). These tests used a set of four square bounded hatched regions, with differing hatch angles as shown in figure 1 below. Please note that no optimisation of the laser mark in terms of laser on / off times was performed.

5.1. Traditional Circle based wobble modes

The basic hatch pattern shown in figure 4 was scanned with the following scanning parameters. Mark speed 1000mm/s, Jump speed 1000 mm/s, Jump delay 15ns, Mark delay 20ns, laser power 10W. Two modes of "traditional wobble" modes were tested, modes 1 and 2. When operating in mode 1 (Constant Linear Mark

Speed with Specified Period) various values of wobble thickness and period were used, the effects of which can be seen in Appendix A (Images E to M). Of note, and shown in figure 5 is that in some cases there appeared to be the possibility to create a rudimentary mesh structure using basic wobble functionality.

In mode 2 (Constant Linear Mark Speed with specified Overlap), using the same scanning parameters used in mode 1 various values of wobble thickness and overlap were tested. Similar to mode 1 some mesh like effects were found to be possible. Effects such as that shown in figure 6 and in Appendix A (Image k), which might conceivably be useful in creating internal mesh type structures within to aid light weighting of parts without having to necessarily design complex lattices. The laser parameters in this test were not optimized. The effect of non-optimized laser on/off delays are evident. It is envisaged that any use of this technique would require suitable bounding to ensure external part geometry is not adversely affected. Please refer to Appendix A (images N to Q) for more test results.

When using modes 1 and 2 the linear velocity of the commanded trajectory remains constant, therefore as expected no variation in execution time was observed. Tangential velocity will change according to the wobble parameters provided.
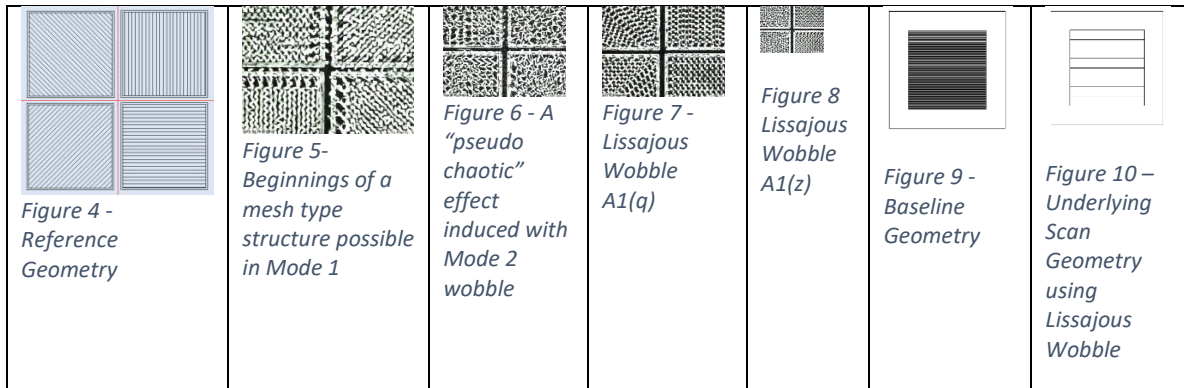
5.2. Lissajous Wobble (Mode 3)

Initially the basic hatch pattern shown in figure 4 was scanned with the following scanning parameters. Mark speed 50mm/s, Jump speed 1000 mm/s, Jump delay 15ns, Mark delay 20ns and various Laser Powers (Typically 10,30,70W).

The study into Lissajous wobble had three specific objectives:
1) To evaluate likely scanning parameters, understand the features sensitivity/adaptability to scanning direction.
2) To understand / seek potential configurations that could yield improvements in scan time and/or improve material properties with different energy profiles.
3) Determine a method to model the energy density likely to be experienced by the material, based on this technique. The intent being to aid scan job developers to better equate use of this scanning technique to the final part quality.

6. Evaluation of Scanning Parameters

Using the reference geometry given in figure 4, many process parameters were explored. Given the limited scope and time available, all 2^7 permutations were not explored. Some interesting mesh type structures were found while testing, in particular those shown in Appendix A (images q and z) and below in figures 7 and 8. The intended use case is the possibility of light weighting of structures. Using Lissajous, the structure is tighter, repeatable and directionally consistent.

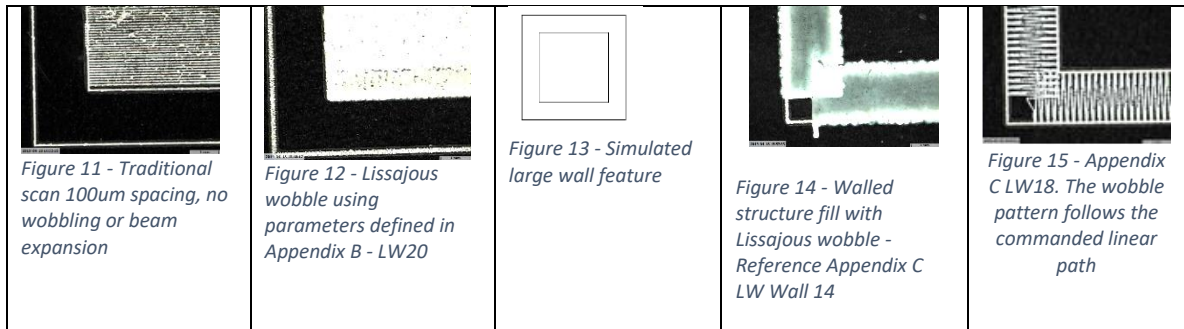|						
Figure 4 - Reference Geometry	*Figure 5- Beginnings of a mesh type structure possible in Mode 1*	*Figure 6 - A "pseudo chaotic" effect induced with Mode 2 wobble*	*Figure 7 - Lissajous Wobble A1(q)*	*Figure 8 Lissajous Wobble A1(z)*	*Figure 9 - Baseline Geometry*	*Figure 10 – Underlying Scan Geometry using Lissajous Wobble*

7. Evaluation of Scan Time

The geometry shown in figure 9 was used as a basis to evaluate whether scan time improvements could be attained. The hatch spacing used was 100um, selected because in a typical additive manufacturing machine the spot size would be larger, fully exposing the enclosed region. The result of executing this pattern are shown in figure 11 and Appendix B(Image titled Reference). When executed the total execution time was 20455ms.

Based on prior work we deduced that it should be possible to reduce/simplify the number for scan lines significantly by using the Lissajous method as shown in figure 10. The author is mindful that in most additive manufacturing applications the machine developer could also elect to expand the spot size. Typically this is limited to 140-160 % of the spot size, using defocusing methods. In this case we considered an effective spot size increase of 2000%, with a track width of 2mm. During testing, the number of hatch lines was increased from 5 to 7 to demonstrate a more even energy exposure.

It is evident from the results presented in Appendix B that the energy density varies. This is expected and discussed in detail later in this paper. Figures 11 and 12 show effects of scanning the geometries referred to in figures 9 and 10 respectively. Of particular note is that Figure 11 took 20455ms to scan whereas figure 12 took 1181ms. This represents a potential reduction of scanning / fill time of 90%. It should however be tempered with the following caveats:
  1) Laser power must be increased
  2) Energy density will vary and needs to be carefully considered in the context of the required part quality

Figure 11 - Traditional scan 100um spacing, no wobbling or beam expansion

Figure 12 - Lissajous wobble using parameters defined in Appendix B - LW20

Figure 13 - Simulated large wall feature

Figure 14 - Walled structure fill with Lissajous wobble - Reference Appendix C LW Wall 14

Figure 15 - Appendix C LW18. The wobble pattern follows the commanded linear path

Often in additive manufacturing, walls need to be built within or as part of the exterior of a structure. Whilst not a thin walled structure per se, the geometry in figure 13 was used as a basis to demonstrate a possible approach to building a walled structure more efficiently and is a precursory work prior to working on a thinner walled, more Additive Manufacturing representative structure. A variety of parameters were tested in the process of determining the most useful/interesting settings to use. Some of these can be found in Appendix C. Using Lissajous wobble to fill, and traditional vector scanning of the interior and exterior walls, thus allowing the developer control over surface quality.

The fully exposed fill regions shown in figure 14 represents the best set of set of parameters initially. Evident from the image is where the Galvos change direction the energy density is higher, leading to higher exposure in the marking shown. This could potentially prove useful in building the wall of walled structures, with the boundary or contour only required for surface quality reasons.

Figure 14 demonstrates a region of overlapped exposure and a region with no exposure. It is anticipated that in a real application of this technique the overlapping region would be avoided and unexposed regions touched up using either traditional scanning techniques or lissajous wobble over a smaller region. Either way scan time reductions can be realized using this technique. The Lissajous wobbling feature developed is direction aware. This means that the wobble pattern changes in synchronously with vector direction as shown in figure 15.
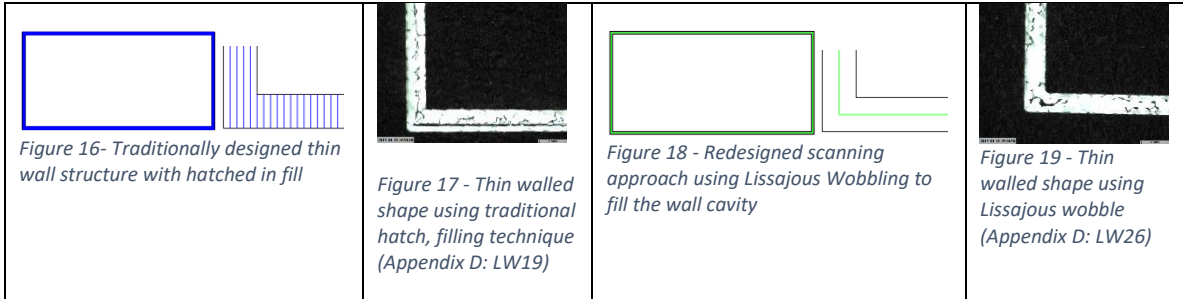
In figure 16 geometry of an example thin walled structure is shown. Below it is a close up view of the internal structure showing that it consists of a simple linear hatch with a hatch spacing of 100um. When this geometry was scanned using a linear mark speed of 50mm/s a scan time of 8780ms was recorded. Figure 17 shows the effect produced when this pattern is run.

Figure 18 reconsiders the scanning approach. We maintain the exterior and interior walls as vector lines allowing the designer to process that part of the structure with surface roughness and other parameters in mind. The fill is taken care of with a single trajectory path, represented by the green line in between the interior and exterior lines of the geometry. When this pattern is executed the time to scan the entire geometry is 457ms, in effect taking approximately 5% of the original scan jobs execution time. The effect observed when the pattern was scanned is shown in figure 19.

When comparing figure 17 and 19 there are two observations that can readily be drawn. First, both appear to have regions that are not fully exposed, and secondary touching up of some regions is likely dependant on process development work in powder. Nethertheless the productivity possibilities are clear.

To gain a better understanding of the Energy Density at the focal point during the scan, the next section of the paper considers the relationship between conventional vector based scanning and lissajous wobble based scanning.

Figure 16- Traditionally designed thin wall structure with hatched in fill

Figure 17 - Thin walled shape using traditional hatch, filling technique (Appendix D: LW19)

Figure 18 - Redesigned scanning approach using Lissajous Wobbling to fill the wall cavity

Figure 19 - Thin walled shape using Lissajous wobble (Appendix D: LW26)

8. Energy Density Considerations

From the results of the lab tests and scan timings, it is evident that the scanner is running faster when scanning more complex patterns. This is expected and desirable as our aim is to increase utilization of the scanner capability. We can infer from this that the energy density is going to be different. In equation 1 we saw that energy density can be defined in terms of scan speed, hatch spacing, laser power and layer thickness. When using more complex command patterns and trajectories, each time interval within the scan pattern needs to be known in order to determine the overall Energy Density distribution. The position of the galvo in radians can be determined by equations 2 and 3.

To evaluate velocity (Vx and Vy) we derive the first order differential of equations 2 and 3 to obtain equations 4 and 5:

$$Vx(t) \; = \; A\omega \cos(\omega t + \phi) \tag{4}$$
$$Vy(t) \; = \; B\omega \cos(\omega t) \tag{5}$$

To determine the actual directional velocity we use Pythagoras as shown in equation 6.

$$Va = \sqrt{Vx^2 + Vy^2} \tag{6}$$

Substituting equation 6 into 7 Linear Speed (Ls) can be determined.

$$Ls = Va \cdot Vd \tag{7}$$

Where Ls is linear speed in m/s, Va is Velocity in radians/sec and Wd is the linear distance from target in metres. The result Ls can be substituted back into the Energy Density equation (equation 1) in place of V as defined below:

$$\mathrm{Ed}(t) = \frac{P}{\mathrm{Ls}(t).\,\mathrm{ht}}$$

(8)

As part of this study we created a model based on the calculations described above. We ran the model based on a selection of the parameters used in testing. Two examples are included within this paper, one simple and one more complex interaction.

Example 1. The model was supplied with the settings X Galvo Amplitude 0.2mm, Y Galvo Amplitude 0.2mm, X Galvo Frequency 0.2KHz, Y Galvo Frequency 0.4KHz, Hatch Spacing 100um, Layer thickness 50um and Working Distance 100mm. The model determined that without wobble enabled, the energy density at 100mm/s would be 60 J/mm^3 . Our simulation of the wobble characteristic found that with rapidly changing acceleration/deceleration and changes in direction the density changes creating a signature pattern of energy deposition as shown in figure 21. This was expected yielding a range of energy densities from 24 to 353 J/mm^3. The question it raises is whether the effect in powder is useful to the process.

Example 2. Taking a more complex set of parameters the model is supplied with the following settings. X Galvo Amplitude 0.2mm, Y Galvo Amplitude 1.4mm, X Galvo Frequency 0.1KHz, Y Galvo Frequency 6.4KHz, Hatch Spacing 0.1mm, Layer Thickness 50um, Working Distance 100mm. In this case the energy densities range from 35 to 2436 J/mm^3. The interesting point of note in this execution of the model was the shape and signature of the energy density map.
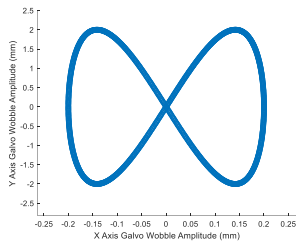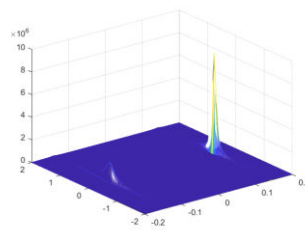

Figure 20 - Galvo position map
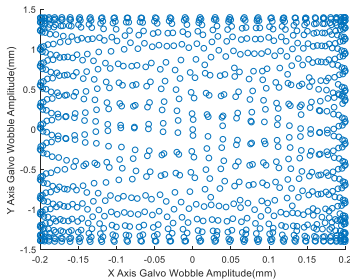

Figure 21 - Energy density prediction

Figure 22 - Galvo position map

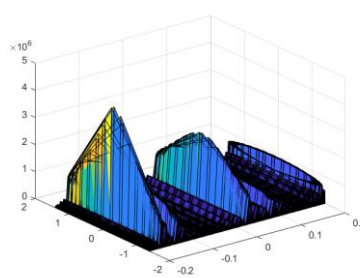Figure 23 - Energy density prediction

9. Conclusions and further work

This paper represents a preliminary study into the potential uses of this feature. It is evident from this study that subject to suitable parameter development and focus there are significant benefits to be yielded from this technique. Energy density has been proven, as expected, to vary. When used in conjunction with advanced wobbling techniques, the apparent presence of a "standing wave" type affect could prove useful in controlling hitherto difficult to control parameters such as the heating and cooling rate. Further work is required.

The author sees future study and development taking several routes including:

(1) Parameter development in powder. Novanta is open to solicitations from additional partners with access and regular use of Laser Based Powder bed Fusion machines, whether from industry or academia, that can help contribute to the body of knowledge pertaining to this technique

(2) Further development of the model built as part of the work undertaken in this study.

(3) Further analysis/study of galvo behavior when operated with Lissajous and other Table based techniques.

(4) Further investigation into whether more determinism of energy density is required.

References

[1] Chun-Yu Tsai, Chung-Wei Cheng, An-Chee Lee, Mi-Ching Tsai , 2019. Synchronized multi-spot scanning strategies for the laser powder bed fusion process

[2] Paul A. Hooper, 2018. Melt pool temperature and cooling rates in laser powder bed fusion

[3] J.C. Heigel, B.M. Lane, 2017. The effect of powder on cooling rate and melt pool length measurements using in situ thermographic techniques

[4] Haider Ali, Hassan Ghadbeigi, Kamran Mumtaz, 2017. Effect of scanning strategies on residual stress and mechanical properties of Selective Laser Melted Ti6A14V

[5]J.Robinson, I.Ashton, P.Fox, E.Jones, C.Sutcliffe,2018. Determination of the effect of scan strategy on residual stress in laser powder bed fusion additive manufacturing

[6] Pavel Hanzl, Miroslav Zetek, Tomas Baksa, Tomas Kroupa, 2014. The Influence of Processing Parameters on the Mechanical Properties of SLM Parts

[7] Bryce Samson, Mustafa Coskun, Giuseppe Barbieri, Franceso Cogini, ENEA-Casaccia Research Center,Rome , Sergio Cassarini, Marco Franzose, IPG Photonics (Italy), 2017. Shop floor Lasers article Heads Up!

[8] Saad A.Khairallah, Andrew T. Anderson, Alexander Rubenchik, Wayne E. King,2016. Laser powder-bed fusion additive manufacturing: Physics of complex melt flow and formation mechanisms of pores, splatter and denudation zones, Acta Materialia : 108(2016)36-45

[9] Manyalibo J.Matthews, Gabe Guss, Saad A. Khairallah, Alexander M. Rubenchik, Philip J. Depond, Wayne E.King, 2016. Denudation of metal powder layers in laser powder bed fusion processes

[10] Hengfeng Gu, Haijun Gong, Deepankar Pai, Khalid Rafi, Thomas Starr, Brent Stucker,2013. 24th Annual Solid Freeform Fabrication Symposium

Appendix A. Test hatches generated using various wobble modes

Constant Linear Speed with Constant Period

	e	f	g	h	i	j	k
Thickness(mm)	0.2	0.2	0.3	0.6	0.6	0.2	1.0
Wobble Period(us)	80	10	10	10	150	150	150

Constant Linear Speed with Constant Period

	l	m
Thickness(mm)	0.2	0.2
Frequency (Hz)	10	10000

Constant Linear Speed with Constant Overlap

	n	o	p	q
Thickness(mm)	0.2	1.0	3.0	1.0
Overlap (%)	80	80	80	99(Power 30%)

Lissajous Wobble Parameters

|	r	s	t	u	v	w	x	z
X Amplitude (mm)	0.2	0.2	0.6	0.8	0.8	0.8	0.8	0.8
Y Amplitude (mm)	0.2	0.2	0.8	0.8	0.8	0.8	0.8	0.8
X Frequency (KHz)	3	3	0.01	0.01	0.1	0.1	0.1	0.1
Y Frequency (KHz)	3	3	3.5	3.5	3.5	3.5	2.0	4.0
φ (Degrees)	10	90	90	90	45	45	45	20
Power (Watts)	30	30	30	30	10	10	10	10

Appendix B. Square reference shape with centre fill using Lissajous wobble

(Reference) (LW15) (LW16) (LW17) (LW18) (LW19) (LW20)

Lissajous Wobble Parameters

	Reference	LW15	LW16	LW17	LW18	LW19	LW20
X Amplitude (mm)	-	0.1	0.2	0.2	0.2	0.2	0.2
Y Amplitude (mm)	-	2.0	2.0	2.0	2.0	2.0	0.4
X Frequency (KHz)	-	0.001	8.2	1	1	1	1
Y Frequency (KHz)	-	1.2	0.4	2	4	1	1
φ (Degrees)	-	135	3	0	0	0	3
Power (%)	5	70	70	70	70	70	70
Number of Pattern Lines	78	4	7	4	4	4	4
Scan Time (ms)	20455	677	1181	677	-	-	1181

Appendix C. Example of wall fill using Lissajous wobble

LW Wall 1 LW Wall 2 LW Wall 5 LW Wall 7 LW Wall 8 LW wall 9 LW Wall 12 LW Wall 14

Lissajous Wobble Parameters

	LW Wall 1	LW Wall 2	LW Wall 5	LW Wall 7	LW Wall 8	LW Wall 9	LW Wall 12	LW Wall 14

X Amplitude (mm)	0.01	0.01	0.01	0.01	0.001	0.001	0.00000001	0.00000001
Y Amplitude (mm)	1.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
X Frequency (KHz)	0.01	0.01	0.001	2.0	0.001	0.001	0.001	0.001
Y Frequency (KHz)	0.2	0.2	0.2	4.0	0.2	0.2	1.2	1.2
ϕ (Degrees)	45	45	10	90	135	45	135	135
Power (%)	10	10	10	10	10	10	50	100

Appendix D. Thin Walled Rectangle
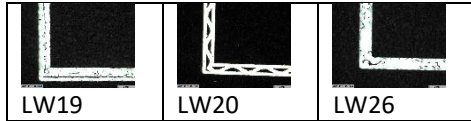
LW19 LW20 LW26

Lissajous Wobble Parameters			
	Reference	LW19	LW20	LW26
X Amplitude (mm)		-	0.2	0.8
Y Amplitude (mm)		-	0.4	0.8
X Frequency (KHz)		-	8.2	0.2
Y Frequency (KHz)		-	0.4	3.0
ϕ (Degrees)		-	3	90
Power (%)		10	70	90
Number of Pattern Lines		390 (0.1um spacing)	n/a	n/a
Scan Time (ms)		8780	457	457