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Challenges in path planning of high energy density beams for additive manufacturing

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Abstract. As there are no cutting forces in High Energy Density (HED) beams like lasers and Electron Beam (EB), their speeds are limited only by their positioning systems. On the other hand, as the entire matrix of the 3D printed part has to be addressed by the thin beam in multiple passes in multiple layers, they have to travel several kilometers in tiny motions. Therefore, the acceleration of the motion system becomes the limiting factor than velocity or precision. The authors have proposed an area-filling strategy for EB to fill the layer with optimal squares to exploit analog and hardware computing. 3D printing requires uniform intensity slanged as flat hat shape whereas the default is Gaussian. The authors have proposed an optimal algorithm that takes into account the maximum velocity and acceleration for achieving a flat hat without any compromise on productivity.

1. Introduction
In milling, the cutter and workpiece are always in contact to cause separation of material using forces (Figure 1a). So, friction at the tool-workpiece interface limits the traversal speeds. Usually, these are not greater than 3 m/min (0.05 m/s). Despite these low speeds, productivity is high as the milling cutters are large. On the other hand, *High Energy Density (HED)* beams like laser and *Electron Beam (EB)* do material removal by energy transfer [1-2]. As they have no physical contact with the workpiece, friction and other forces are absent (Figure 1 b&c). Therefore, they can move at extremely high speeds limited only by their positioning systems. On the other hand, HED beams are used in focused conditions to have adequate energy density and hence have a very low diameter. Therefore, they need to make several passes to address any given area. Two broad applications of HED beams are:
  i. Joining, cutting, engraving, etc.
  ii. Additive Manufacturing (AM).

Table 2 summarizes the features of both these applications. While Gaussian energy distribution is favorable for the first group of applications, AM will require a uniform or flat hat shape as area-filling is essentially akin to paint-brushing (See Figure 2). While laser can achieve flat hat beam characteristic (i) optically or (ii) through oscillation, this is achievable only through oscillation in EB [1-4].
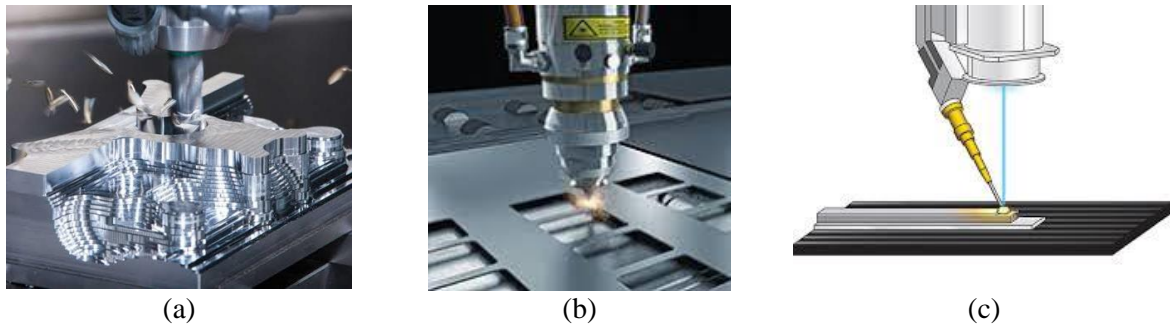

| (a) | (b) | (c) |

Figure 1. Contact and non-contact tools in manufacturing: (a) Contact tool in CNC machining; (b) Laser cutting; (c) Electron beam cladding. (b) and (c) are non-contact tools: HED beams

Table 1 Comparison of contact and non-contact tools in manufacturing

Feature	Manufacturing Using	
	Cutters	HED Beams
Physical contact and transfer of forces	Present	Absent
Speed of interaction	Extremely low	Extremely high
Diameter at interaction	Extremely high	Extremely low

Table 2 Comparison of the two broad applications of the HED beams in manufacturing

Feature	Joining/ Cutting/ Engraving	Additive manufacturing (AM)
Length of travel	Only contouring. So, short lengths.	Contouring as well as area filling. So, very long paths.
Number of passes of sintering/ Melting	Usually a single pass.	Multiple passes to gradual & uniform heating to minimize the residual stresses and warpages.
Motion accuracy	Low (0.080 to 0.100 mm will do)	
Speed of travel	Very less to allow sufficient time for melting – of the order of 1,000 to 5,000 mm/min (0.017-0.085 m/s).	Extremely high – 20 m/s possible for lasers using galvanometer; 10,000 m/s for EB using deflection coils.
Acceleration of travel	It can be very low – as a low as 5 m/s^2 will do.	It has to be extremely high due to short rasters.
Beam profile	Gaussian	Flat hat (uniform)

The build time in any 3D printing process using HED beam will be proportional to its volume. The part is built from thousands of slices. The regions in each slice defined by loops will have to be filled by moving the thin beam along millions of segments of sizes varying from a fraction of a millimeter to a few hundred millimeters. Furthermore, these motions may be straight lines (along X or Y or at any arbitrary orientation) or curvilinear.
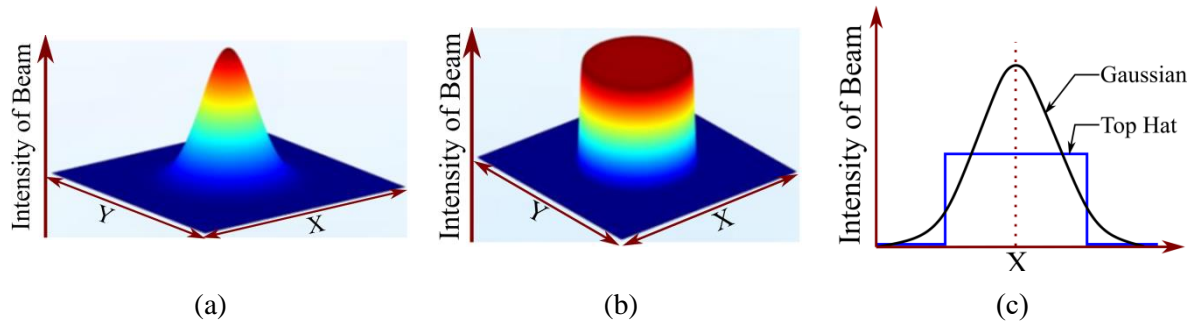

| (a) | (b) | (c) |

Figure 2. Gaussian and flat hat shapes of the HED Beams: (a) Gaussian; (b) Flat hat; (c) Both shown superimposed.

Table 3. Comparison of popular motion systems.

Motion system	Surface of focus	Spot size	Repeat-ability	Velocity	Acceleration	Application
Rotary motor with belt & pulley	Flat	Circular	±25μm	10 m/s	0.5g	Both.
Rotary motor with leadscrew & nut	Flat	Circular	±15μm	2 m/s	0.5g	For lasers, the lens can be moved.
Linear motors	Flat	Circular	±5μm	7 m/s	30-100g	For EB, the only table can be moved.
Galvanometers	Spherical	Oval	±15μm	10 m/s	> 5000g	Only for lasers
Deflection coils	Spherical	Oval	±15μm	$> 10^4$ m/s	$> 10^4$ g	Only for EB

Note: The values are the only representative for the purpose of qualitative comparison. 1 g = 10 m/s2 approx.

In summary, the thin HED beam in AM, capable of extremely high speeds and accelerations, has to be moved quickly along kilometers of distances constituted by short/long and straight/curvilinear segments. In order to achieve this, the following aspects deserve serious attention:

    i.   Motion system
    ii.   Path planning algorithm
   iii.   Scanning patterns and direction
    iv. On/off switching of the beam
    v.   Beam shape
   vi. Preference of hardware and analog systems to digital systems.
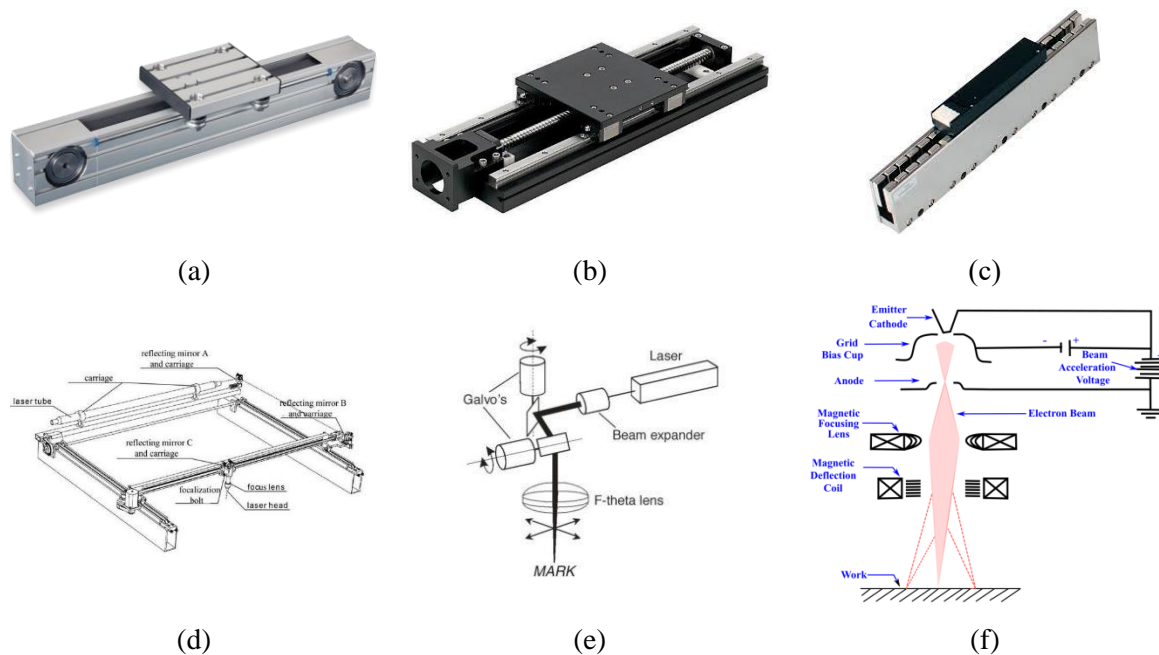
Figure 3. Popular motion systems: (a) Belt driven; (b) Screw driven: (c) Linear motor system; (d) Flying optics: (e) Galvanometer; (f) Deflection coils. (a) and (b) are rotary motor systems. (d) and (e) are motion controls specific to lasers. (f) is a motion control specific to EB.

2. Motion systems

Various possible motion systems are illustrated in Figure 3. Their performances are compared in Table 3. Consider a 20mm cube to be built by a beam of 0.5mm diameter in layers of 0.25mm. Assuming 75% stepover of a beam in consecutive passes, the total length of motion will be $\frac{20}{0.25}$ layers x 20mm x $\frac{20}{0.5*0.75}$ passes = 85/333mm. Assuming a speed of 2m/s for a motion system using leadscrew, this can be made in about 43 seconds. But, this is under the assumption that the velocity is constantly at 2m/s. This is not possible in reality as the motor has to ramp up from rest to reach the maximum speed, cruise at that speed and then ramp down to rest again in each of the 20mm segments. Therefore, for an acceleration of 5m/s^2, the maximum speed will never be reached; it will be only $\sqrt{2 * 5 * 0.010} = 0.31623$ m/s. So, the average speed will be half of this, i.e., 0.15811 m/s. So, although the maximum velocity is 2 m/s, because of the low acceleration, the average velocity is only 0.15811 m/s. Therefore, the building will take $\frac{85.333}{0.15811} = 550$ seconds instead of just 43 seconds. In order to keep the focus on motion analysis, we choose to ignore here the inter-layer overhead time for table movement, material spreading, etc. which are substantial (10 seconds to 1 minute per layer). Since the motions will be often as small as 1mm, the acceleration of the motion system becomes the most important parameters in 3D printing. Since 3D printing has two inherent errors due to (a) stair-step way of growing and (b) support removal, repeatability of about 0.04mm is good enough. The maximum velocity of even 2m/s is adequate as long as it is achievable. As is seen from Table 3, the maximum velocities of all the motion systems listed are adequate. Therefore, the selection of the motion system in 3D printing using the HED beam is exclusively dictated by its acceleration.

Manufacturing requires relative motion which can be achieved either by moving the tool or the workpiece on the table. Table movement is usually through the rotary motor and hence will be slower. Therefore, it is desirable to move the HED beam wherever possible.

2.1. Motion system for lasers

Due to the low inertia of the tiny oscillating mirrors, the galvanometer is able to deflect the beam at extremely high speeds and accelerations. As illustrated in Figure 3 and Table 3, the galvanometer is the

best in terms of accelerations – over 5000g, which is about 100 times that of linear motors. But linear motors have accelerations higher by 50 times existing rotary motor systems. Therefore, they are a good compromise between galvanometers and rotary motors. We prefer linear motors to galvanometers because:

- Galvanometers are affordable only up to 1.5kW power which is well below future requirements in 3D printing of over 4kW power; efficient path planning algorithm is able to distribute uniformly the enormous heat without warpages.
- Galvanometers suffer spot geometry variations in size and shape (circle to ovality) at different (x, y) locations; correcting these errors optically is difficult and expensive.
- Galvanometers are more expensive than linear motors today.

2.2. *Motion System for EB*

As the deflection of EB is achieved by controlling the current flow in the coils, it is totally free from mechanical inertia [1]. Assume an EB of 1mm diameter at a height of 500mm from the current layer. It is possible to oscillate the beam over a range of ±30º at a frequency of 10 kHz. So, its scanning speed can be as high as $\frac{\pi}{3} * 0.5m * 2 * 10kHz \approx 10,000$ m/s. Its acceleration too can be much greater than 10,000 m/s². These values are 1,000 times that of laser!
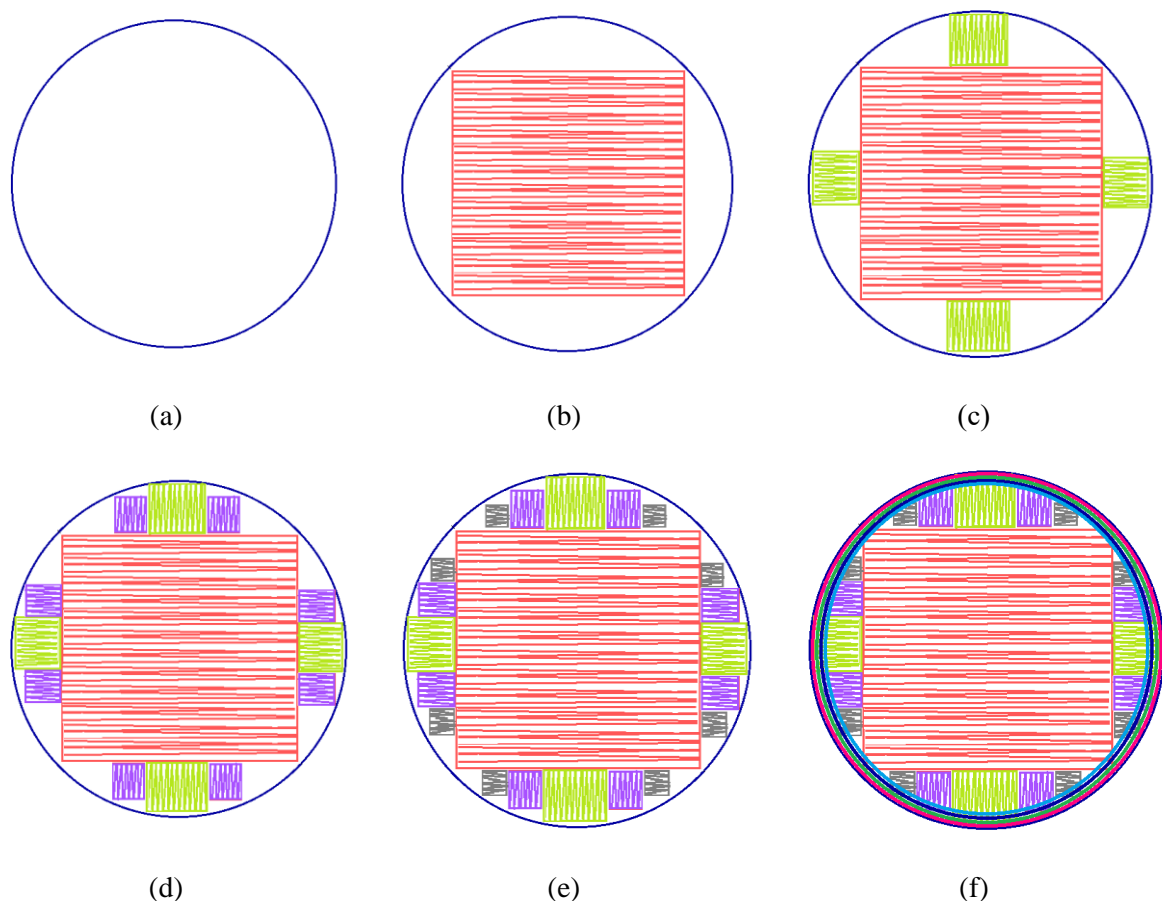

Figure 4. Area-filling using squares: (a) Circle to filled, (b) The 1st level of filling with squares; (c) The 2nd level of filling with squares; (d) The 3rd level of filling with squares; (e) The 4th level of filling with squares; (f) Final filling with contours.

While EB can be deflected at such phenomenal speeds, other related things too should match to exploit it. If we try to run EB along a boundary or fill it with raster lines, the digital computation of CNC

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and its interpolators comes into the picture. These digital computations take much higher time compared to the time scales that EB takes to cover a few millimeters. Therefore, we should replace digital computing with analog and hardware. So, the traditional area-filling strategies like *direction-parallel*, *contour-parallel*, *space-filling curves*, *traveling salesman algorithm,* etc. will not work for EB. Instead, the region should be divided into squares (or rectangles) of different sizes. Each square (x_c, y_c, s) shall be scanned using an analog circuit that generates appropriate saw tooth waves for X and Y coils and their biases to fill it. Finally, the contour itself may be offset by the required number of times to fill the rest of the area. Figure 4 demonstrates this area-filling concept for a circular region. Each square is filled in a sawtooth form is illustrated.

2.3. HED beam on/off
The on/off switching time of the HED beam is slow compared to the beam deflection speed. So, instant on/off does not happen to result in huge profile errors in area-fill. Therefore, we propose to switch on EB at the beginning of a layer and switch it off only after the entire layer is over. We implemented this for laser in sand 3D printing and found it satisfactory.

2.4. Scanning path and directions for HED beam
Any CNC interpolation takes time. Hence, even when the same speed is fed through a program, the results produced on the workpiece will be very different. This was very evident in the experiments carried out on thin sheet metal processing using lasers. As it is shown in Figure 5, while scanning over the diagonal of the rectangle, the speed of laser becomes less due to interpolation resulting in more heat input compared to sides of the rectangle. Even though appropriate offsets in speed during path generation can produce desired results, that leads to compromise over the utilization of speed we can achieve with HED beams. Furthermore, curvilinear motions of contour-parallel area-filling patterns suffer centrifugal forces in addition to higher computing time. Therefore, we use rasters along X and Y in alternate layers.

Figure 5. Effect of CNC interpolation on laser processing of thin sheets.

2.5. Segmentation of path of HED beam
The aspect ratio is the highest in 3D printing as compared to many manufacturing processes as building happens in thin layers. This results in warpages and residual stresses. Therefore, we have developed an algorithm that will segment the tool path into segments of certain fixed length, say 200mm; each segment is picked randomly and scanned. Thus, the heat input will be more uniform resulting in minimum residual stresses and warpages. Figure 6 demonstrates the segmented approach of area filling.
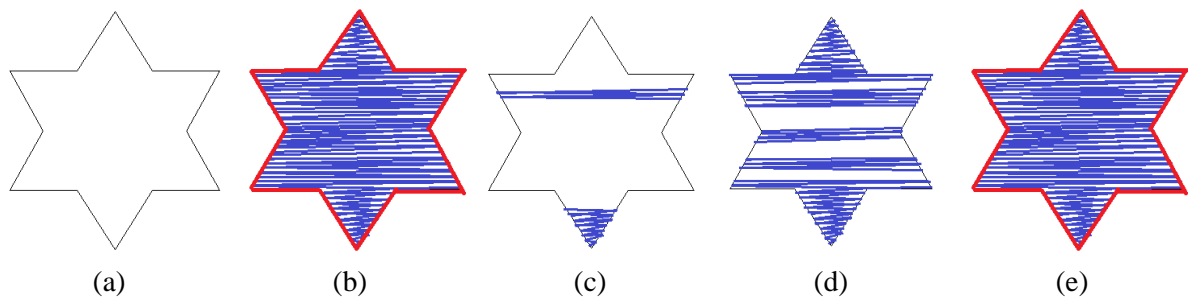
(a)   (b)   (c)   (d)   (e)

Figure 6. Random segmentation of area-filling motions to achieve uniform heat distribution: (a) Contour; (b) Area-filling path: (c), (d), (e) random writing of the segments.

3. Path planning to achieve flat hat beam profile and minimize build time

Although the concepts of this section are generic, the discussions here are in the context of laser beam positioning using flying optics driven by linear motors. The following are the two goals here:

   i.   Flat hat beam profile

   ii.   Minimization of scanning time

Flat hat profile is achieved in lasers optically using beam homogenizer. Another simpler way is to oscillate the beam in the transverse direction as shown in Figure 7a, which leads to consecutive Gaussian forms overlapping as in Figure 7b. As we move either on X or Y during area-filling, oscillation can be done along the other direction. The velocity of both the motors can be chosen such that about 75% stepover of the consecutive Gaussian forms will happen which is a reasonable approximation of flat hat.

However, this will mean that the motor in the oscillating direction (Y here) will be used more efficiently compared to that of the traveling direction (X here). We are keen to exploit both motors at the highest possible speeds so that the build time will be less and at the same time, the consecutive Gaussians will overlap to give a flat hat beam.
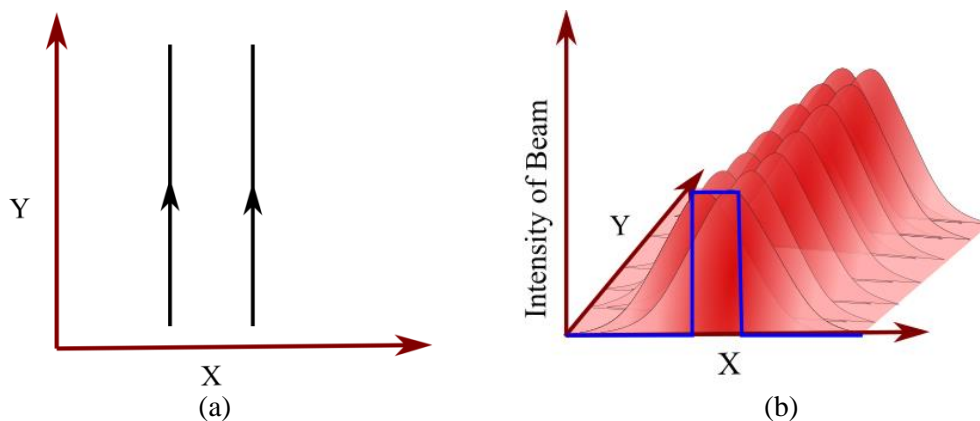

(a)   (b)

Figure 7. Oscillation to achieve flat hat: (a) Oscillation pattern; (b) overlapping Gaussian leading to flat hat
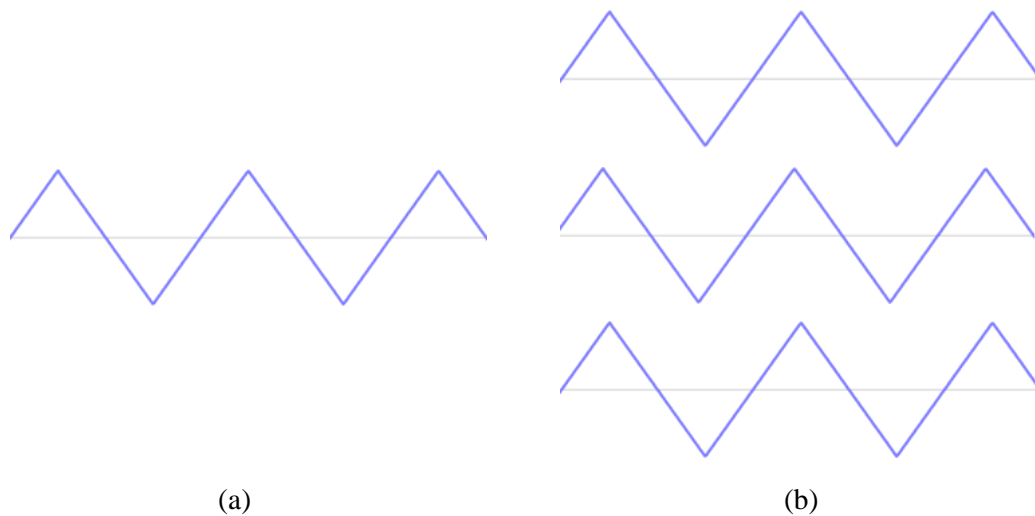
| (a) | (b) |

Figure 8. Oscillation with equal speeds of the axes: (a) Single-pass; (b) Multiple passes with the flat hat.

When both axes are moved at maximum possible equal speeds, then, the result will be a triangular wave with a 45º angle as shown in Figure 8a. Instead of getting Gaussians overlapped between the consecutive oscillations as it is shown in Figure 7b, we shall tweak the starting and ending points of the area-fill raster so that the triangular waveforms of the consecutive passes match as shown in Figure 8b. This would achieve the required flat hat without any compromise on the build rate.
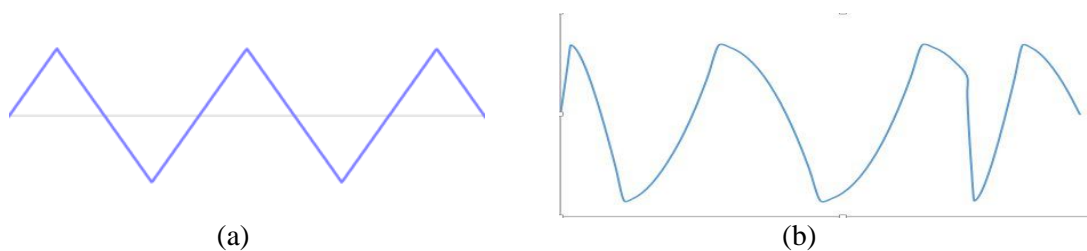

| (a) | (b) |

Figure 9. Oscillation with equal speeds of the axes – (a) theoretical and (b) real paths.

The path shown in Figures 8a and 9a are theoretical assuming the same velocity for X and Y. However, their velocities may not be equal always. Furthermore, as the oscillation amplitude is less, the maximum attainable speed in Y-axis will be less than X-axis. Thus, the real path will be distorted as shown in Figure 9b.

This was tested in a case study presented in Figure 10 for a circle. Its rasters are shown in Figure 10a. When we used the exact points of the raster, the waves do not match as shown in Figure 10b and thus flat hat was lost. However, after appropriate tweaking of the endpoints, the waves matched as shown in Figure 8c. Note that the endpoints now fall in a grid of the working envelope. Therefore, area-filling is less complete. However, this can be handled by adding more contouring passes similar to the approach adopted in the square-based area-filling proposed for EB (Figure 4f).
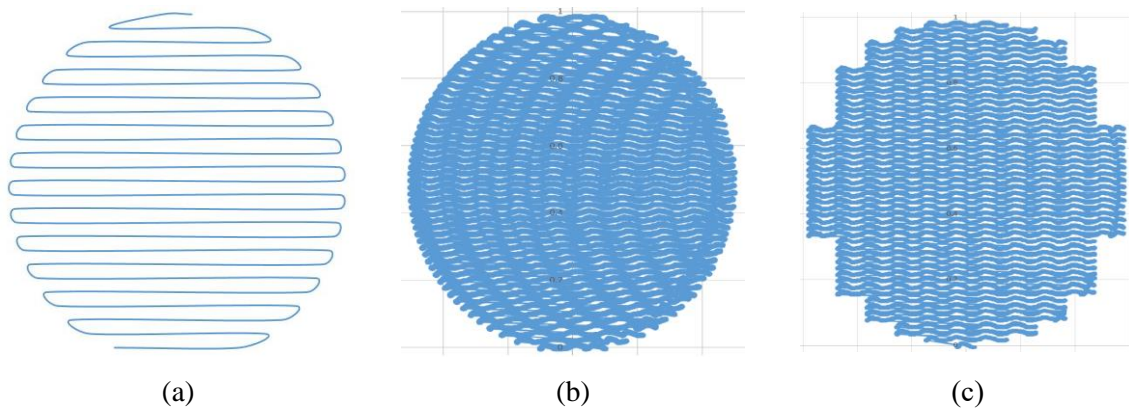
| (a) | (b) | (c) |

Figure 10. Case study of a circle: (a) Circle with rasters; (b) Area-fill without tweaking of the endpoints resulting in the loss of flat hat; (c) Area-fill with suitable tweaking of the endpoints resulting in a flat hat.

CAM packages are mostly geometric processors and rarely take into account the kinematics and dynamics of the process. In the 3D printing processes using any HED beam, we need to incorporate these parameters, viz., the maximum velocity and acceleration, during path planning.

4. Conclusions

The manufacturing speed in machining is limited by friction but it is limited by only the positioning system in 3D printers using the HED beam as there are no forces. As there are millions of tiny motions, the acceleration becomes the limiting factor than velocity or precision. The importance of a flat hat beam for 3D printing was demonstrated. In order to achieve a flat hat beam without any compromise on productivity, two path planning algorithms were proposed, one each specific to EB and laser, the former exploiting analog and hardware computing and the latter taking into account the maximum velocity and acceleration of the motion system.

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