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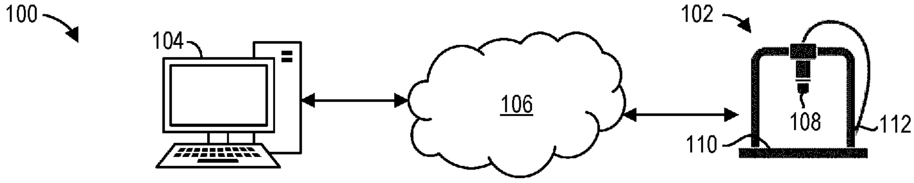

FIG. 1

(57) Abstract: Disclosed are methods and systems for manufacturing a polymer-based part using additive manufacturing by (a) generating a plurality of horizontally slices of a virtual three-dimensional (3D) part model; (b) for each horizontal slice, determining a slice-specific toolpath configuration to generate a continuous overlapped and interwoven toolpath pattern for that slice; and (c) manufacturing the part by operating an additive manufacturing system according to the slice-specific toolpath configuration for each layer.

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METHOD AND SYSTEM FOR MANUFACTURING INTERWOVEN POLYMER-BASED PARTS USING ADDITIVE MANUFACTURING

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. provisional patent application serial no. 63/433,336, filed on December 16, 2022, the entire contents of which are hereby incorporated by reference.

FIELD

[0002] The present invention generally relates to additive manufacturing techniques. More particularly, disclosed embodiments relate to a method and system for manufacturing polymer-based parts using additive manufacturing using an interweave technique.

BACKGROUND

[0003] Conventional manufacturing of composite parts is a skillful and tedious process that can take many hours to process, depending on the size of the part. Wet lay-up, prepreg lamination, and resin transfer molding represent the three main processes used to produce such parts. In each case, the part is manufactured using a multistep process with significant lead times.

[0004] Additive manufacturing (AM), also known as 3D printing, is a fast-emerging field and may facilitate such production. A challenge of AM focuses on manufacturing composite materials with less lead time, as well as improved mechanical and structural properties for the printed part.

SUMMARY OF VARIOUS EMBODIMENTS

[0005] Embodiments herein generally relate to a method and system for manufacturing polymer-based parts using additive manufacturing.

[0006] The disclosed method generally involves, initially, vertically slicing a computer model of the to-be-printed part into *n* horizontal cross-sectional layers. For each slice, a horizontal envelope is determined, and if concave, the envelope is then divided into a number of convex subareas based on the layer thickness of the deposited material. For each convex area or subarea, an overlapping and/or interweaving zig-zag toolpath with at least four paths per slice is computed. Each of the four paths is either offset from or is oriented in a different direction from at least one of the other paths. By dividing the horizontal envelope into multiple convex subareas, the continuity of the zig-zag path inside each convex subarea is guaranteed. All the zig-zag paths are then linked together using a boundary layer as a direction. In other words, the bridges between the zig-zag paths correspond to a portion of the boundary layer. Preferably the bridges are offset from each other to avoid massive overlapping.

[0007] In at least one embodiment, for each toolpath, a “lower layers awareness” map is determined to avoid collision between the nozzle of the additive manufacturing (AM) system, and the previously deposited matrix. This map encodes the vertical motion of the nozzle according to the average height of material deposited in its close neighborhood.

[0008] In accordance with the above, in at least one broad aspect, there is provided a method for manufacturing a polymer-based part using additive manufacturing comprising: generating a plurality of horizontally sliced layers of a virtual three-dimensional (3D) part model, wherein the virtual 3D part model extends along a printing axis, and the horizontally sliced layers are defined in horizontal planes orthogonal to the printing axis, and wherein the plurality of horizontal layers extend, along the printing axis, between a first printable layer and a last printable layer; for each horizontal slice, determining one or more envelope boundaries, wherein the envelopes define at least one printable cross-sectional area, corresponding to a non-void area of the 3D part in that horizontal slice; for each horizontal slice, determining a slice-specific toolpath pattern, wherein each slice-specific toolpath pattern defines a continuous overlapped and interwoven toolpath pattern for that slice, and covering the printable area for that slice; and manufacturing the part by operating an additive manufacturing (AM) system according to the slice-specific toolpath pattern for each slice layer, wherein the 3D part model is printed, one slice at a time, from the first printable layer to the last printable layer, along the printing axis.

[0009] In some examples, the AM system is configured to print in a first and a second toolpath printing direction.

[0010] In some examples, the first and second toolpath directions are orthogonal to each other, along a horizontal slice plane.

[0011] In some examples, the printing axis defines a vertical Z-axis, and the first and second toolpath directions are defined in the X- and Y-axis directions.

[0012] In some examples, determining the slice-specific toolpath pattern for a given horizontal slice comprises: in respect of the first toolpath direction, determining a corresponding first and second continuous toolpath pattern, each pattern comprising a zig-zag extending along the first toolpath direction and covering the printable cross-sectional area; in respect of the second toolpath direction, determining a corresponding first and second continuous toolpath pattern in the second toolpath direction, each pattern comprising a zig-zag extending along the second toolpath direction and covering the printable cross-sectional area; generating an overlaid toolpath pattern, the overlaid pattern comprising a superimposed overlaying of the toolpath patterns determined for each toolpath direction, wherein the toolpath patterns are overlaid, over each other, in a direction of the printing axis, and wherein the printable areas, represented in each toolpath pattern, are orientationally aligned; and generating one or more connective toolpaths that link between the overlaid toolpath patterns, to generate the slice-specific toolpath pattern, defining a continuous overlapped and interwoven toolpath pattern for that slice.

[0013] In some examples, in respect of each toolpath direction, the second continuous toolpath pattern is offset relative to the first continuous toolpath pattern, wherein the offset is defined such that, when the second continuous toolpath pattern is overlaid, along the printing axis, over the first continuous toolpath pattern, the second pattern includes a zig-zag toolpath positioned between adjacent path lines of the first path zig-zag, when viewed along the printing axis.

[0014] In some examples, the toolpaths are overlaid, along the printing axis, in the overlaid toolpath pattern, in accordance with the following overlaid order: (a) the first continuous toolpath determined for the first toolpath direction; (b) the first continuous toolpath determined for the second toolpath direction; (c) the second continuous toolpath determined for the first toolpath direction; and (d) the second continuous toolpath determined for the second toolpath direction, wherein (a) defines the lower-most toolpath, and (d) defines the upper-most toolpath, along the printing axis.

[0015] In some examples, for a given toolpath direction, determining the corresponding first and second continuous toolpath patterns, initially comprises: determining whether the at least one printable area, for the horizontal slice, is a concave or convex are, relative to the toolpath direction, wherein the printable area is a convex area if a continuous zig-zag toolpath is generatable, along the toolpath direction, within the printable area without any discontinuity zones, and wherein the printable area is a concave area if a continuous zig-zag toolpath is not generatable, along the toolpath direction, within the printable area, and based on the determination, determining the first and second continuous toolpath patterns.

[0016] In some examples, if the at least one printable area is determined to be concave, relative to the toolpath direction, then determining the corresponding first and second continuous toolpath patterns further comprises: segmenting the concave area into two or more convex subareas relative to the toolpath direction; for each convex subarea, determining a first and second toolpath zig-zag pattern, along the printing direction; determining one or more first linking paths connecting between each of the first toolpath patterns, of each convex subarea, to generate the first continuous toolpath pattern; and determining one or more second linking paths connecting between each of the second toolpath patterns, of each convex subarea, to generate the second continuous toolpath pattern.

[0017] In some examples, segmenting the concave area into two or more convex subareas comprises: superimposing a plurality of rays over the horizontal slice, each ray extending along the toolpath direction; in respect of each ray, determining the number of intersection points between the ray and the envelope for the horizontal layer; if the number of intersections is higher than two for a given ray, then in respect of that ray, identifying pairs of intersection points separated by an outside of the printable cross-sectional area; determining intermediate points that are equally distally spaced between each pair of intersection points; and linking, all intermediate points, aligned along a line orthogonal to the rays, to segment the concave area into multiple local convex subareas.

[0018] In some examples,, a boundary envelope will be concave in at least a first horizontal direction and in a second horizontal direction which is substantially at a right angle to the first horizontal direction. Each concave boundary envelope is then divided into at least two convex subareas, resulting in four convex subareas which overlap.

[0019] In some examples,, the toolpath configuration comprises at least one boundary envelope layer. The first to fourth paths are connected with a link path which preferably lies on a boundary envelope layer.

[0020] In another broad aspect, there is provided a system for manufacturing a polymer-based part using additive manufacturing comprising: a deposition assembly, of an additive manufacturing (AM) system, for extruding filament material to manufacture a 3D part component; and at least one processor coupled to the deposition assembly, and configured for to preform any or all of the above.

[0021] Other features and advantages of the present application will become apparent from the following detailed description taken together with the accompanying drawings. It should be understood, however, that the detailed description and the specific examples, while indicating preferred embodiments of the application, are given by way of illustration only, since various changes and modifications within the spirit and scope of the application will become apparent to those skilled in the art from this detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

[0022] For a better understanding of the various embodiments described herein, and to show more clearly how these various embodiments may be carried into effect, reference will be made, by way of example, to the accompanying drawings which show at least one example embodiment, and which are now described. The drawings are not intended to limit the scope of the teachings described herein.

[0023] Figure 1 is an example system for additive manufacturing.

[0024] Figure 2 are example virtual or computerized three-dimensional (3D) models of a Stanford bunny and a double nut structure.

[0025] Figure 3A is a process flow for an example method for additive manufacturing of polymer-based three-dimensional (3D) parts.

[0026] Figure 3B is a process flow for an example method for determining a slice-specific toolpath configuration for additive manufacturing.

[0027] Figure 4 is a horizontally sliced 3D part model of the example Stanford bunny and double nut structures.

[0028] Figure 5 is a horizontal cross-sectional slice of the double nut structure, showing internal and external boundaries.

[0029] Figure 6A is a horizontal cross-sectional slice of the Stanford bunny, showing a zig-zagging toolpath along the X-axis direction.

[0030] Figure 6B is a horizontal cross-sectional slice of the Stanford bunny, showing one or more X-direction local convex subareas.

[0031] Figure 7A is a horizontal cross-sectional slice of the Stanford bunny, showing a zig-zagging toolpath along the Y-axis direction.

[0032] Figure 7B is a horizontal cross-sectional slice of the Stanford bunny, showing one or more local Y-direction convex subareas.

[0033] Figure 8A is a horizontal cross-sectional slice of the double nut structure, showing one or more local X-direction convex subareas.

[0034] Figure 8B is a horizontal cross-sectional slice of the double nut structure, showing one or more local Y-direction convex subareas.

[0035] Figure 9A shows a horizontal cross-sectional slice of the Stanford bunny, and showing first and second zig-zagging toolpath configurations, oriented in the X-direction, within local convex subareas.

[0036] Figure 9B shows a horizontal cross-sectional slice of the Stanford bunny, and showing first and second zig-zagging toolpath configurations, oriented in the Y-direction, within local convex subareas.

[0037] Figure 10A shows a horizontal cross-sectional slice of the double nut structure, and showing first zig-zagging toolpath configurations, oriented in the X and Y directions, within local convex subareas.

[0038] Figure 10B shows a horizontal cross-sectional slice of the double nut structure, and showing second zig-zagging toolpath configurations, oriented in the X and Y directions, within local convex subareas.

[0039] Figure 11A show horizontal cross-sectional slices, of a Stanford bunny, and showing a linking bridge toolpath.

[0040] Figure 11B show horizontal cross-sectional slices, of a Stanford bunny, and showing a linking bridge toolpath.

[0041] Figure 11C is a schematic illustration of an example overlapping and interweaving pattern for a horizontal slice whereby interweave is obtained at the end of 4^{th} layer.

[0042] Figure 11D is a 3D visualization of an example overlapping and interweave pattern for a horizontal slice showing the interwoven print.

[0043] Figure 12 show horizontal cross-sectional slices, of a Stanford bunny and double nut structure, and showing an overlapping and interweaving toolpath with boundary layers, where the different paths overlap and interweave.

[0044] Figure 13 show horizontal cross-sectional slices, of a Stanford bunny and double nut structure, and showing artifacts of a continuous overlapping and interweaving toolpath.

[0045] Figure 14A show horizontal cross-sectional slices, of a Stanford bunny and double nut structure, and showing ray casting to determine convex areas in the X-direction.

[0046] Figure 14B show horizontal cross-sectional slices, of a Stanford bunny and double nut structure, and showing ray casting to determine convex areas in the Y-direction.

[0047] Figure 15 show various horizontal cross-sectional slices, of a Stanford bunny and double nut structure, and showing a modified zig-zag toolpath.

[0048] Figure 16 show various horizontal cross-sectional slices, of a Stanford bunny and double nut structure, and showing a modified overlapping continuous toolpath.

[0049] Figure 17A is an example simplified hardware block diagram for an example additive manufacturing (AM) system.

[0050] Figure 17B is an example simplified hardware block diagram for an example computer terminal.

[0051] Further aspects and features of the example embodiments described herein will appear from the following description taken together with the accompanying drawings.

DETAILED DESCRIPTION OF THE EMBODIMENTS

[0052] Embodiments described below generally relate to methods and systems for manufacturing of polymer-based parts using additive manufacturing. The disclosed embodiments provide a method and system for enabling additive manufacturing of polymer-based parts using a continuous overlapping toolpath.

I. DEFINITIONS

[0053] Any term or expression not expressly defined herein shall have its commonly accepted definition understood by a person skilled in the art. As used herein, the following terms have the following meanings.

[0054] "Additive Manufacturing" is generally known in the art, and refers to a set of manufacturing techniques which involve depositing layer-by-layer material to create a net shape part. In many cases, the manufacturing or building process is based on a virtual model generally generated using computer assisted design (CAD). Examples of additive manufacturing include three-dimensional (3D) printing and rapid prototyping. "Computer Aided Manufacturing" (CAM) is the use of computer-controlled machinery to automate a manufacturing process.

[0055] "Composite Material (CM)" is a material which is produced from two or more constituent materials.

[0056] "Polymer Matrix Composite (PMC)" is generally known in the art as a composite material composed of a variety of fibers bound together by a matrix of organic polymers. The load carrying fibers can be formed of Kevlar, Aramid, carbon fiber, glass fiber or any syntactic or naturally occurring fiber, only by way of non-limiting examples. The corresponding matrix of organic polymers can be, for example, polyester resin, epoxy resin, and thermoplastics like polylactide (PLA).

[0057] "Polymers" are a class of natural or synthetic substances composed of large molecules, i.e., macromolecules, which are multiples of simpler chemical units, i.e., monomers.

[0058] "Polymer-based material" refers herein to polymer and/or polymer composite materials.

[0059] "Processor" refers to one or more electronic devices that is/are capable of reading and executing instructions stored on a memory to perform operations on data, which may be stored on a memory or provided in a data signal. The term "processor" includes a plurality of physically discrete, operatively connected devices despite use of the term in the singular. Non-limiting examples of processors include devices referred to as microprocessors, microcontrollers, central processing units (CPU), and digital signal processors.

[0060] "Memory" refers to a non-transitory tangible computer-readable medium for storing information in a format readable by a processor, and/or instructions readable by a processor to implement an algorithm. The term "memory" includes a plurality of physically discrete, operatively connected devices despite use of the term in the singular. Non-limiting types of memory include solid-state, optical, and magnetic computer readable media. Memory may be non-volatile or volatile. Instructions stored by a memory may be based on a plurality of programming languages known in the art, with non-limiting examples including the C, C++, Python ™, MATLAB ™, and Java ™ programming languages.

II. GENERAL OVERVIEW

[0061] While carbon fiber composite materials have many advantageous properties, manufacturing carbon fiber parts is challenging because of the complexity of manufacturing. In general, carbon fiber parts are manufactured using various techniques, including wet lay-up, prepreg lamination and resin transfer molding.

[0062] All of these processes share the same base material, which is a fiber sheet. A carbon fiber sheet consists of weaves with different patterns, such as plain weave, twill weave, or satin weaves offering different properties such as stability and flexibility. In each case, the parts manufactured using wet lay-up, prepreg lamination or resin transfer use a multistep process with significant lead times.

[0063] Additive manufacturing (AM) involves depositing layer-by-layer material to manufacture a net shape part. The building process is based on a virtual model generally created using computer assisted design. Thanks to this method, it is possible to generate internal features and multidirectional prints. When combined with physical data, one can modify the physical, thermal, and mechanical properties of the part.

[0064] The advantages of carbon fibers can be combined with the ones of AM, such as 3D printed carbon fiber parts. In most cases, the carbon fiber parts are produced using a filament containing macroscopic fibers wet into a polymer such as PLA (Polylactic acid), ABS (Acrylonitrile Butadiene Styrene) or PEEK (Polyether Ether Ketone). These parts generally offer better properties than commonly 3D printed parts.

[0065] Nevertheless, the performance of these AM techniques are still limited compared to traditional carbon manufactured parts using long carbon fibers deposited in an overlapped fashion. More particularly, existing techniques are limited to either printing carbon fiber filaments using tiny fibers that are infused into a base, or printing hollow structures with a semi continuous path of long fibers. Each of these techniques requires custom molds and supports.

[0066] Accordingly, there is a desire to explore options for continuous printing of parts using long carbon fibers with a single continuous toolpath overlapped. The overlapping main interests of printing with a continuous material flow (i.e., continuous overlapped patterns) are to increase the mechanical properties of the part and reduce the energy and time needed to print the part. A continuous overlapped path minimizes the number of discontinuities (i.e., places where the filament is cut), thereby enhancing structural properties of the printed part.

[0067] In view of the foregoing, embodiments herein generally relate to a method and system for manufacturing of polymer-based parts using additive manufacturing.

[0068] The disclosed embodiments allow for controlling the toolpath of an additive manufacturing system to enable planar and non-planar continuous overlapping printing of a polymer-based material. Disclosed methods combine continuity overlapping inside a single slicing process customized for additive manufacturing. In at least one embodiment, the method involves determining a parametric continuous path with infill and boundary layers for 3D printing of polymer matrices, or polymer matrix composite. In some embodiments, the methods comprise a continuous printing of a part using long carbon fibers with a single continuous toolpath.

[0069] The continuous path provides overlapping deposition of infill lines to produce an interwoven result. The continuous path does not include an "over-under" pattern of adjacent lines, which is the hallmark of a true woven pattern. Instead, the continuous path provides overlapping lines which approximates a woven pattern, as described further below. The continuous path is non-planar in that each path layer overlaps vertically with a previous path layer.

[0070] As used herein, the term "interweave" or "interwoven" in the context of additive manufacturing or 3D printing, means planning for material extrusion, or directed energy deposition homogenous polymer, or polymer composite 3D print process in a sequential manner whereby, due to interaction between two (2) or more multiple passes of the material extrusion processes, an interweave between the polymer and/or fibers is created.

[0071] In some examples, the disclosed methods allow manufacturing of medium to high volume parts with significant bead thickness and bead height (e.g., 1 to 10 mm of diameter).

[0072] While the discussion herein primarily focuses on manufacturing parts with polymer composite materials using carbon fibers – it is appreciated that this is only one example application, and the same principles and concepts can be applied to printing with any other polymer and/or polymer composite material.

[0073] It is believed that the disclosed methods may ease manufacturing complexity, time and costs of medium to large volume 3D parts while preserving the properties of the materials known for their stiffness, low weight to strength ratio, high temperature tolerance, low thermal expansion and high chemical resistance.

III. EXAMPLE SYSTEM CONFIGURATION

[0074] Figure 1 shows an example system (100) for additive manufacturing of polymer-based parts, in accordance with embodiments described herein.

[0075] As shown, system (100) generally includes an additive manufacturing (AM) system (102). In some examples, AM system (102) is coupled to a computer terminal (104), via communication network (106). AM system (102) can also couple to an external server, via network (106) (not shown).

[0076] In at least one example, AM system (102) is a three-dimensional (3D) printer. More generally, as is known in the art, the AM system (102) is able to deposit layer-by-layer materials to generate geometric structures in three-dimensions (3D).

[0077] In disclosed embodiments, the AM system (102) is used to deposit and manufacture 3D parts using polymer-based materials. The following description focuses on a non-limiting example application where the AM system (102) is used for manufacturing parts using a carbon fiber polymer matrix.

[0078] As described, the AM system (102) can receive input data for a 3D object. The input data can correspond to a computerized or digital 3D object model. For example, this can include a 3D computer-aided-design (CAD) model of the target part. Figure 2 shows example parts that can be manufactured using the AM system (102). These include a model of a Stanford bunny (200a) and a double nut (200b) structure.

[0079] As known in the art, the AM system (102) may include a deposition assembly (108) comprising a nozzle head, extruder and the like. The deposition assembly (108) can deposit the layer-by-layer material on a printing platform (110). In some examples, the deposition assembly (108) is mounted to a support structure (112).

[0080] As described herein, the AM system (102) may also include various other components. These may include various driving subsystems (e.g., stepper motors), power sources, control systems, displays, deposit supplies, single or multi-material extruder, or a composite polymer matrix fiber extruder etc. In at least one example, the AM system (102) is a 3- to 8-axis machine.

[0081] System (100) can also include the computer terminal (104). The computer terminal (104) can provide an interface for user(s) to generate, receive and/or store the input modelling data for the 3D part requiring manufacturing. The input data is then transmitted to the additive manufacturing (AM) system (102) for manufacturing.

[0082] As described further on, with reference to Figure 17B, the computer terminal (104) can generally include a processor (1702b) coupled to a memory (1704b), a display interface (1706b), an input interface (1708b), and a communication interface (1710b).

[0083] In other examples, system (100) may not necessarily include the computer terminal (104). For example, the AM system (102) may itself include its own input and display interface for user interaction. In still other examples, in addition or in alternative to computer terminal (104), system (100) can include one or more servers for storing and transmitting the input 3D data to the AM system (102).

[0084] Communication network (106) can be an internet, or intranet network. In some examples, network (106) may be connected to the internet. Typically, the connection between network (106) and the internet may be made via a firewall server (not shown). In some cases, there may be multiple links or firewalls, or both, between network (106) and the Internet. Some organizations may operate multiple networks (106) or virtual networks (106), which can be internetworked or isolated. These have been omitted for ease of illustration, however it will be understood that the teachings herein can be applied to such systems. Network (106) may be constructed from one or more computer network technologies, such as IEEE 802.3 (Ethernet), IEEE 802.11 and similar technologies. Alternatively, the computer (104) may be connected to the AM system (102) by any commercially available short range communication protocol, such as Bluetooth™ or the like.

IV. EXAMPLE METHOD(S)

[0085] The following is a description of example methods for manufacturing of parts from polymer-based materials (e.g., carbon fiber composite materials) using additive manufacturing. The methods enable additive manufacturing using a continuous overlapping toolpath. In turn, the methods allow for manufacturing parts with enhanced mechanical, structural and physical properties.

[0086] Figure 3A shows one embodiment of a process flow for an example method (300a) for additive manufacturing of three-dimensional (3D) parts. In some examples, the entirety of method (300a) is performed by the additive manufacturing (AM) system (102).

[0087] As shown, at act (302a), input three-dimensional (3D) part model data is accessed. The input data corresponds to the 3D part requiring manufacturing. The input data can include a geometric definition of the 3D object, as well as derived geometric metadata. This can include various wireframes, surfaces or solids that may be represented in any fashion.

[0088] In some examples, the input data is a CAD model, such as a Standard Triangle Language (STL) file. The creation and use of suitable input data is well known in the art, and is not an element of the claimed invention.

[0089] In at least one example, the input 3D data is stored and accessed on a memory of the additive manufacturing (AM) system (102). In other examples, the input 3D data is received from an external source by the AM system (102). For instance, the external source can be the computer terminal (104), external server(s), or any other computing device or system.

[0090] At act (304a), various printing parameters are determined for the additive manufacturing process. For example, the printing parameters can include: (i) layer thickness of deposited material; (ii) bead height; and/or (iii) bead thickness. Other parameters can include various design parameters including the number of boundary layers, percentage of infill, number of paths per layer. These design parameters are explained in greater detail below.

[0091] The printing parameters, at act (304a), can be configurable, user-selectable, or user-adjustable. In other examples, however, at least some of the printing parameters are fixed or pre-defined.

[0092] At act (306a), the input 3D part model is sliced (or segmented) into one or more horizontal slices. In this manner, the 3D part model is segmented into "n" horizontal slices (e.g., one or more, or a plurality of horizontal slices).

[0093] As used herein, "vertical" refers to an axis, or plane, extending upwardly and downwardly. In other words, a vertical axis or plane extends between a bottom end and top end of the 3D part model. During manufacturing, the 3D object is printed by depositing layer-by-layer in the vertical direction to build the part from the bottom to the top. The vertical axis is also referred to herein interchangeably as a “printing axis”, as it corresponds to the axis along which the 3D part is printed by the AM system (102). In contrast, the "horizontal" axis, or plane, is defined in an axis orthogonal to the vertical axis or plane (or printing axis or plane). In disclosed embodiments, each horizontal slice will comprise a plurality of path layers.

[0094] As shown in Figure 4, the 3D part models – of the example Stanford bunny (200a) and double nut (200b) – are each sliced (or segmented) into a plurality of horizontal slices (402).

[0095] As shown, the horizontal slicing occurs orthogonal to the printing axis (450), and parallel to the horizontal axis, defined along the reference horizontal Cartesian X-Y-plane. The vertical Z-axis (e.g., printing axis (450)) extends between the bottom end (404a) and the top end (404b) of each 3D part model. Each horizontal slice represents a cross-section of the 3D object, along the X-Y horizontal plane.

[0096] Accordingly, in manufacturing the 3D part, each horizontal slice represents a separate, and distinct layer deposited by the additive manufacturing (AM) system (102). As provided herein, each horizontal slice is deposited using a continuous overlapping toolpath pattern.

[0097] In some examples, the plurality of horizontal layer slices (402), generated at (306a), extend, along the printing axis (450), between a first printable layer and a last printable layer, e.g., in the order in which they are printed by AM system (102). The first printable layer defines the bottom end (404a) of the 3D part model, and the last printable layer defines the top end (404b) of the 3D part model.

[0098] In at least one example, the number of horizontal slices is generated based on the known, or pre-defined deposition layer height. In some examples, the layer height is taken as a multiple $\gamma<1$ of the actual layer height. Regarding a pre-defined layer height, the four paths defining the layer are firstly overlapped with an offset γ time layer height with $\gamma <1$. To avoid any collision during the printing process, the height awareness map is also computed, and the vertical position of each point of the four paths is modified giving the wavy aspect of the final printing path.

[0099] At act (308a), a slice-specific toolpath pattern (or toolpath configuration) is determined, for each horizontal slice (402). The toolpath configuration, for each slice, provides a movement pattern for the deposition assembly (108), of AM system (102) (Figure 1). The movement pattern is defined in the XY plane (e.g., the plane orthogonal to the printing axis (450)).

[00100] In embodiments herein, the toolpath pattern or configuration, for each layer, comprises a parametric continuous path defined by a zig-zag and overlapping pattern. Each subsequent layer results in a "quasi-interweave" with the layer immediately deposited below. In some examples, each toolpath pattern, for each layer, comprises four overlapping zig-zag patterns, as disclosed below.

[00101] At act (310a), the additive manufacturing (AM) system (102) is operated in accordance with a toolpath configuration determined for each of the "*n*" horizontal slices. In this manner, the AM system (102) manufactures the 3D object, slice-by-slice (e.g., along printing axis (450)). For example, this involves operating the tool face subsystem (1706a) (FIG. 17A), of the AM system (102), which controls the spatial motion path of the deposition assembly (108) to follow the determined toolpath for each horizontal slice.

[00102] In some embodiments, the AM system (102) is able to deposit all of the constituent slices of the 3D part in a continuous path (i.e., without discontinuities). That is, the continuous deposition is not only performed within each slice – but also, between consecutively and vertically stacked slices.

[00103] As used herein, a "continuous path" refers to the ability to operate the AM's deposition assembly (108), such that the deposition assembly (108) is able to continuously extrude filament material without stopping the extrusion. For example, the deposition assembly (108) does not require stopping the deposition to be relocated to a different spatial position, before continuing extruding filament.

[00104] Figure 3B shows one embodiment of a process flow for an example method (300b) for determining a layer-specific toolpath configuration. Method (300b) expands on act (308a), of method (300a).

[00105] As shown, at act (302b), for a given horizontal slice – at least an external two-dimensional (2D) boundary envelope of that slice is determined, wherein the 2D boundary envelope is defined in the horizontal plane (e.g., orthogonal to printing axis (450)). If present, at least one internal boundary envelope of the slice is also identified.

[00106] As used herein, a "boundary" or "envelope" refers to a set of points organized in a sequenced manner. Each point is linked to its previous and next neighbors by segments forming a line set.

[00107] In at least one example, to determine one or more boundary envelopes at (302b), the system uses the intersections between a horizontal plane at layer "k", and the part, to compute the 2D boundaries of the part at layer "k". The system can consider both the external and internal boundaries, and can organize them into a graph so that the offset direction is always known.

[00108] To further clarify this concept, reference is made to Figure 5, which shows an example 2D layer (500) for the double nut structure (200b). As shown, the respective internal boundaries (502) and external boundaries (504) are identified, e.g., based on where the spaces (e.g., voids) around and within the part are located at that horizontal layer.

[00109] At (304b), one or more closed printable cross-sectional areas are determined, based on the determined boundary envelopes (also referred to herein as, “printable areas” or “printable cross-sectional areas”).

[00110] More generally, the envelope boundaries – determined for a given horizontal slice – define (e.g., enclose) one or more closed printable areas, corresponding to a non-void area of the 3D part in that horizontal slice. Each printable area (550), within a given horizontal layer, is fully bounded by one or more envelopes, along the horizontal plane.

[00111] More generally, a printable area defines an area of the horizontal slice that requires printing using filament material. For example, this refers to printable area (550) for the double nut structure (FIG. 5), and printable area (550) for the Stanford bunny structure (FIGs. 6 – 7).

[00112] At (306b), the computed printable cross-sectional area(s) are also determined (e.g., classified and/or identified) to be either concave or convex, relative to the known pre-defined deposited bead thickness.

[00113] As used herein, a printable area (550) is considered "concave" if it is impossible to generate a toolpath for the deposition assembly (108), along a given toolpath printing direction, that covers the entirety of the printable area (550), for a given slice layer, with a continuous linear "zig-zag" path with a thickness equal to the bead thickness. In contrast, a "convex" printable area can be filled with a continuous, uninterrupted zig-zag path with a thickness equal to the bead thickness.

[00114] As used herein, a zig-zag path refers to a pattern that includes one or more extending linear line portions, whereby adjacent line portions are connected together by curved connecting portions, as known in the art.

[00115] Further, as used herein, a toolpath printing direction (or simply, a “printing direction” or “toolpath direction”) refers to a direction, defined along the horizontal slice plane, along which the deposition assembly (108) translates along the linear portions of a zig-zag pattern, in order to deposit material within the printable area (550) (e.g., X-axis and/or Y-axis, or at any angle thereof). The toolpath printing directions may be pre-defined for the AM system, or otherwise, user-selectable. In some examples, to allow for the desired interweaving pattern, the disclosed embodiments allow for two toolpath printing directions, which are orthogonal to each other in the horizontal plane (e.g., orthogonal to the printing axis (450)), e.g., X-axis and Y-axis directions.

[00116] Figures 6A and 7A show a single horizontal slice of the Stanford bunny (200a), and further clarifies the difference between “concave” and “convex” printable areas.

[00117] In Figure 6A, it is assumed that the slice is "printed" by moving the AM system (102) toolpath in a linear zig-zag path along the X-axis (e.g., front to back). In contrast, in Figure 7A, the layer is "printed" by moving the toolpath in a linear zig-zag path along the Y-axis (e.g., left to right).

[00118] As provided below, each horizontal layer can be printed along both the X- and Y- axis directions. Generating zig-zags in both the X-direction and the Y-direction allows forming the slice from an overlapping pattern. That is, the overlapping is generated by operating the nozzle toolpath – of the AM system (102) – in both the X-direction and the Y-direction. As provided previously, generating a slice comprising continuous overlapping patterns enhances the mechanical and structural properties of the 3D part.

[00119] With respect to Figure 6A, the printable area (550), defined by envelope (602a), is considered "concave" at act (304b) when the toolpath is moved along the X-axis. This is because it is

not possible to fill the entirety of the printable area (550) with a continuous zig-zag path, along the X-axis.

[00120] To be more specific, in the printable subarea (604a), it is possible to operate the toolpath in the X-axis, and along a continuous, uninterrupted zig-zag toolpath. This is represented by the arrows (606a). In contrast, the printable subarea (608a) forms a discontinuity zone, which prevents operating the toolpath in a continuous, uninterrupted linear manner. For this reason, printable area (550) is therefore considered "concave" in the X-direction, e.g., as it is not possible to generate a continuous path, along the X-axis, that fills-in (e.g., covers) the entirety of the printable area (550).

[00121] In Figure 7A, the same printable area (550) (as in FIG. 6A), is again considered "concave" if the toolpath is now operated linearly in the Y-direction (i.e., zig-zagging from left to right).

[00122] For example, while a continuous path (706a) is generated in the subarea (704a), a discontinuity zone (708a) prevents forming a continuous path along the entirety of the printable area (550). Therefore, the printable area (550) is also considered a concave envelope with respect to the Y-direction.

[00123] Accordingly, in some examples, to determine whether the printable area (550) is concave in a given printing direction, the system can determine if one or more discontinuity zones exist.

[00124] As used herein, a discontinuity zone (or discontinuity region) refers to a subarea, of the printable area (550), which prevents operating the toolpath, in a given printing direction, along a continuous path along the entirety of the printable area (550). In other words, in a discontinuity zone, the toolpath cannot operate continuously (e.g., in a continuous zig-zag pattern), along a given printing direction, while maintaining the toolpath within the boundary envelope(s) defining the printable area (550), and without otherwise overlapping (or re-overlapping) over an area (or subarea) that was previously covered by the toolpath.

[00125] To this end, determining whether a printable area (550), is "concave" versus "convex" is a direction-specific determination. In other words, at act (306b), a separate determination is made as to whether: (i) the printable area (550) is concave if the toolpath is operated in the first printing direction (e.g., X-direction); and (ii) the printable area (550) is concave if the toolpath is operated in the second printing direction (e.g., Y-direction). The same determination is also made if the toolpath

is operated in any other direction (e.g., at a non-right angle to the X or Y axis, in the XY plane). A printable area (550) can be concave in one direction, but convex in another direction. Accordingly, the determination at (306b) can be made for each printing direction used, for a given horizontal layer, as well as for each printable area (550) within the horizontal layer.

[00126] In some examples, at (306b), the system can therefore determine the toolpath printing directions used by the AM system (102). The system may then determine, for each printable area (550) within the horizontal layer, whether that printable area (550) is concave or convex, with respect to each toolpath printing direction.

[00127] Returning to Figure 3B, at (308b), based on the determination at (306b), the system determines if a printable area (550) is concave in a given printing direction (e.g., X- and/or Y-direction). If the printable area (550) is determined to be concave in a given printing direction – then at act (310b), at least two local convex printable subareas are determined for that toolpath direction. That is, the concave printable cross-sectional area is segmented into at least two local convex subareas, for that printing direction.

[00128] As explained herein, the at least two convex subareas are defined such as to remove (e.g., eliminate) any discontinuity zones, in the horizontal layer, for a given printing direction. This facilitates the desired continuous printing path.

[00129] For example, in Figure 6B, at least two local convex subareas (602b), (604b) are determined for the X-direction. As shown, the convex subareas (602b), (604b) eliminate the discontinuity zone (608a). In turn, it is now possible to generate a continuous, uninterrupted zig-zag toolpath pattern within each of the printable subareas (602b), (604b) (*see* e.g., $900a_1$ and $900a_2$ in Figure 9A). Therefore, these areas are now referenced as "convex" subareas while operating the tool along the X-axis.

[00130] Similarly, in Figure 7B, one or more local convex subareas (702b), (704b) are determined for the Y-direction. Again, the convex subareas (702b), (704b) eliminate the discontinuity zone (708a). Therefore, it is now again possible to generate a continuous, uninterrupted toolpath pattern within each of printable subareas (702b), (704b) (*see* e.g., $900b_1$ and $900b_2$ in Figure 9B). Accordingly, each of these area is referenced as "convex" subarea when operating the toolpath in the Y-axis.

[00131] Once again, it will be understood that determining local convex subareas – at act (308b) – is also direction-specific, for a given toolpath printing direction.

[00132] For example, Figure 6B shows direction-specific convex subareas (602b), (604b) for the X-direction. Further, Figure 7B shows direction-specific convex subareas (602b), (604b) for the Y-direction. Therefore, as used herein, "direction-specific convex subareas" are convex printable subareas associated with a particular toolpath printing direction.

[00133] In view of the foregoing, in Figure 3B, at act (308b), if a concave area is determined for the toolpath in the X-direction (Figure 6A) – then one or more direction-specific convex subareas are determined for the X-direction (Figure 6B) (act (310b)). Alternatively, or in addition, if a concave area is determined for the Y-direction (Figure 7A) (act (308b)) – then one or more direction-specific convex subareas are determined for the Y-direction (Figure 7B) (act (3010b)). In turn, acts (306b) and (308b) require separate determinations for each toolpath direction, and for each printable area (550) defined in the layer.

[00134] For additional clarity, reference is made to Figures 8A and 8B, which further exemplify acts (308b) and (310b), but for the double nut structure. Each of these figures shows a cross-sectional envelope (802) for the double nut structure.

[00135] As shown, in each of the X- and Y-directions, the printable area (550), defined by envelope (802), is determined to be concave because it is not possible to generate a continuous, uninterrupted zig-zag pattern in either direction. In this example, however, there are multiple discontinuity zones, at least in the X-direction.

[00136] Accordingly, as shown in (800a) in Figure 8A – in the X-direction, the concave area (550) is segmented into a plurality of direction-specific convex subareas (804a) – (810a). Within each convex subarea (804a) – (810a), it is possible to generate a continuous zig-zag pattern in the X-direction (*see* e.g., toolpath pattern $1000a_1$ in Figure 10A).

[00137] Similarly, as shown in (800b) in Figure 8B, in the Y-direction, the concave area (550) is again segmented into one or more direction-specific local convex subareas (804b), (806b). Within each convex subarea (804b), (806b) it is possible to generate a continuous zig-zag pattern in the Y-direction (*see* e.g., toolpath pattern $1000a_2$ in Figure 10B).

[00138] Continuing with reference to Figure 3B, at act (312b), for each direction-specific convex subarea, one or more sets of toolpath pattern configurations are determined.

[00139] In some examples, for each printing direction – the one or more sets of toolpath pattern configurations include first and second toolpath patterns, which are oriented in that printing direction. In at least one example, the second toolpath pattern is offset from the first toolpath pattern, such that the first toolpath pattern is a “non-offset” pattern, and the second tool path pattern is an “offset” pattern (as explained below).

[00140] To clarify this concept, reference is made to Figures 9A and 9B, which again show the cross-section of the Stanford bunny (200a).

[00141] Figure 9A shows the local convex subareas (602b), (604b) generated for the X-direction (e.g., Figure 6B).

[00142] As shown, in ($900a_1$), at act (312b) – a first toolpath pattern or configuration is determined in the X-direction. This toolpath pattern is determined for each local convex subarea (602b), (604b), and covers the entire area (based on the determined bead thickness). Preferably, the zig-zag pattern begins and ends at the layer envelope.

[00143] As shown, in ($900a_2$) a second toolpath configuration is also determined, at act (310b), in the X-direction, for each convex subarea (602b), (604b). In some examples, the path is determined with an offset equal to the bead thickness.

[00144] As used herein, "offset" means that the path is not directly superimposed on top of another path (e.g., along printing axis (450)), or in other words, the path is positioned between adjacent lines of another path, when viewed vertically. Preferably, the amount of offset is substantially equal to ½ the distance between adjacent lines of the zig-zag path.

[00145] As used herein, the first toolpath in ($900a_1$) is referenced as a "non-offset" path, while the second path in ($900a_2$) is referenced as a "with offset" path. As explained below, generating two toolpath patterns in the X-direction (and subsequently, for the Y-direction), enables generating the desired overlapping pattern.

[00146] In at least one example, at act (312b), to generate the zig-zag pattern – ray casting in the toolpath printing direction (e.g., X-direction) is applied to obtain intersections with the envelope

boundary, of each convex subarea, at equal distances from each other. All the points, for consecutive rays, are then linked together to form a zig-zag toolpath (e.g., linked with curved portions).

[00147] Figure 9B shows the convex subareas (702b), (704b) generated for the Y-direction (e.g., Figure 7B). Again, in ($900b_1$), a first "non-offset" toolpath zig-zag pattern is determined for each convex subarea (702b), (704b) in the Y-direction. Further, at ($900b_2$), a second "with offset" toolpath pattern is determined for each convex subarea (702a), (702b), also for the Y-direction.

[00148] As noted, the four zig-zag paths ($900a_1$), ($900a_2$), ($900b_1$), ($900b_2$) are combined to enable overlapping to generate the overlapped layer for that horizontal slice.

[00149] Figures 10A to 10B illustrate a similar process for a horizontal slice of the double nut structure (200b).

[00150] To that end, Figure 10A shows a first "non-offset" toolpath determined for the X-direction ($1000a_1$) within the concave subareas (804a) – (810a). Further, a first "non-offset" toolpath is also determined in the Y-direction ($1000a_2$) for each of the concave subareas (804b) – (806b). Figure 10B shows a second "with offset" toolpath determined for both the X-direction ($1000b_1$) and the Y-direction ($1000b_2$).

[00151] Referring back to Figure 3B, at act (314b), for each set of direction-specific convex subareas being printed in the same direction (e.g., along same toolpath direction), in the same horizontal layer, and having a common (e.g., same) toolpath pattern configuration (e.g., offset versus non-offset) – one or more linking paths are determined to connect between these convex subareas. These allows connecting these convex subareas in a single continuous toolpath, along a given toolpath direction.

[00152] By way of example, Figure 11A shows a horizontal cross-section of the Stanford bunny (200a). As shown, ($900a_1$) shows the convex subareas (602b), (604b) filled-in with the first "non-offset" zig-zag toolpath, in the X-direction (Figure 9A).

[00153] In this example, at act (314b), a linking path (1102) is determined to connect the toolpaths between the convex subareas (602b), (604b). In this manner, a continuous toolpath is now generated in the X-direction between the two convex areas (602b), (604b).

[00154] For example, the continuous path can: (i) start at boundary point (1150a), (ii) zig-zag through convex area (602b), (iii) continue through linking path (1102a); (iv) zig-zag through convex

area (604b); and (v) terminate at end point (1152a). Alternatively, the continuous path can traverse in the reverse direction, such that it starts at point (1152a) and terminates at point (1150a).

[00155] In Figure 11A, envelope ($900b_1$) shows the convex subareas (702b), (704b) filled-in (e.g., entirely filled-in) with the first "non-offset" toolpath pattern, in the Y-direction (Figure 9B).

[00156] As used herein through-out, “entirely” or “completely” filling-in an area or subarea, means the totality of the area or subarea is covered by the toolpath pattern, having regard to the pre-defined bead thickness of the AM system (102).

[00157] Again, at act (314b), a linking path (1104) is identified to connect the toolpath between the convex subareas (702b), (704b). Accordingly, the system generates a continuous toolpath between the convex subareas (702b), (704b). In turn, a continuous and uninterrupted toolpath in the Y-direction is generated for the entire horizontal slice.

[00158] While not shown, a similar linking path is also determined for the second "with offset" toolpath pattern configuration ($900a_2$), ($900b_2$). This is also generated for both the X-direction and Y-direction toolpaths.

[00159] Once act (314b) is completed, the method has now generated four continuous toolpath patterns: (i) a first toolpath direction (e.g., X-direction) with no offset ($900a_1$ in FIG. 11A); (ii) the first toolpath direction (e.g., X-direction) with offset (not shown); (iii) a second toolpath direction (e.g., Y-direction) with no offset ($900b_1$ in Figure 11A); (iv) the second toolpath direction (e.g., Y-direction) with offset (not shown). As explained previously, each of these direction-specific linked, or continuous toolpath patterns can be combined to generate the overlapped pattern for the horizontal layer.

[00160] With reference to Figure 11B, a similar concept is also shown for the double nut structure. As shown, ($1000a_1$) shows each local convex subarea – in the X-direction – filled-in using the first "non-offset" toolpath configuration. Linking paths (1102b) – (1106b) are identified to connect the multiple toolpaths between each convex subarea (804a) – (810a). Accordingly, a single uninterrupted toolpath is resolved, linking all convex subareas in the X-direction.

[00161] Similarly, ($1000b_1$) shows each sub-convex area – in the Y-direction – filled-in using the first "non-offset" toolpath configuration. A linking path (1108b) is identified to connect the

toolpaths between the two convex subareas (804b) – (806b). Accordingly, a single uninterrupted toolpath is resolved, linking all convex subareas in the Y-direction.

[00162] To this end, at act (314b), the linking paths can be determined in any manner. In at least one example, the linking paths are determined by using the end point of the toolpath for one convex subarea, and the closest entry point of the next convex subarea, e.g., an entry point referring to a terminal path point touching or nearest-adjacent the envelope boundary. The next entry point can be at the initial start or end of the toolpath for that convex subarea. If the closest entry point correspond to the initial end of the toolpath in the next subarea, the sequence of points forming the toolpath of the next subarea is then inverted. In this manner, it can be said that each toolpath pattern represents an ordered sequence of points.

[00163] As shown in Figure 11B, act (314b) can be performed using any number of convex subareas. In these case, any number of linking paths are determined to connect all convex subareas in one continuous path. Accordingly, some convex areas may link at both ends (1150a), (1152a) to separate and adjacent (i.e., neighboring) convex areas.

[00164] Returning to Figure 3B, if at act (308b), the printable area (550) is not determined to be concave for a given toolpath direction (e.g., X or Y direction), then the printable area (550) is determined to be convex in that direction. Accordingly, in that case, method (300b) can immediately perform act (316b).

[00165] At act (316b), the method involves simply determining a zig-zag pattern – in that toolpath direction – within that convex area. For example, the entire convex are is filled-in with an X-direction or Y-direction zig-zag toolpath. This is similar to act (312b), but without using local convex subareas. In some examples, similar to act (316b), at least two toolpaths are also determined at (316b) in a given printing direction (e.g., with offset and without offset).

[00166] In the case of act (316b), since there are no convex subareas (e.g., the entire area is convex), it is not necessary to determine "linking paths" in the manner disclosed at (314b).

[00167] Notably, even if act (316b) is performed in one printing direction, and acts (310b) – (314b) are performed in a different printing direction, the totality of method (300b) can still generate at least four continuous toolpath patterns.

[00168] For example, if the envelope is convex in the X-direction, act (316b) can generate two continuous toolpath patterns in the X-direction (e.g., with and without offset). Further, if the envelope is concave in the Y-direction, then acts (310b) – (314b) can generate two further continuous toolpaths in the Y-direction (e.g., with and without offset). The opposite scenario is also possible with respect to the X- and Y-directions.

[00169] At act (318b), the final overlapped toolpath pattern, shown in Figure 12A, is generated by connecting the multiple direction-specific toolpaths. That is, the toolpaths are overlaid each other in the vertical or Z-direction (e.g., printing axis (450)), and connected to each other. The toolpaths are overlaid such that the envelope boundaries, delineated around each toolpath (and therefore, the printable areas), are aligned and matched along printing axis (450).

[00170] For instance, in at least one example, act (318b) involves vertically stacking (e.g., along printing axis (450)), and connecting the toolpaths in the following order: (i) the first continuous path in the first toolpath direction (e.g., X-direction) without offset (e.g., $1000a_1$ in Figure 10A) is connected to, (ii) the second continuous path in the second toolpath direction (e.g., Y-direction) without offset ($1000a_2$ in Figure 10A) is connected to, (iii) the third continuous path in the first toolpath direction (e.g., X-direction) with an offset equal to the bead height ($1000b_1$ in Figure 10B) is connected to, (iv) the fourth continuous path in the second toolpath direction (e.g., Y-direction) with an offset equal to the bead height ($1000b_2$ in Figure 10B).

[00171] Accordingly, along printing axis (450) – the first path represents the vertically lower-most layer, while the fourth path represents the vertically upper-most layer within the slice. The result is shown schematically in Figures 11C and 11D, where the first and third paths overlap vertically with the second path, while the second and fourth paths overlap vertically with the third path. Each of the four paths thus overlap horizontally with a horizontal offset between the first and third paths and the second and fourth paths respectively, and overlap vertically.

[00172] To connect the paths, the boundary envelope(s) may again be used, as previously explained, and implemented with offsets. To that end, reference is made to Figure 12, where in (1200a), the Stanford bunny is shown with the in-fill layer (1202a) and the boundary layer (1202b). A similar illustration is shown in (1200b) for the double nut structure.

[00173] The in-fill layer (1202a) comprises the multiple, overlapping toolpaths in either toolpath direction (e.g., X- and Y-directions). These are also referenced herein as "in-fill toolpaths".

The boundary layer (1202b) surrounds the in-fill layer (1202a), and defines the outer envelope of the horizontal slice, and corresponds to the boundary envelopes of the horizontal slice.

[00174] The boundary layer, itself, can comprise multiple "boundary toolpaths" (1204) – (1208). For example, each boundary toolpath can link two of the in-fill toolpaths together (e.g., first path to second path; second path to third path; third path to fourth path, etc.). For example, the boundary toolpaths can connect the starting or terminating points (1150a), (1152a) of overlaid in-fill toolpaths (Figure 11A). Accordingly, the in-fill toolpaths are connected together at the boundary.

[00175] In at least one example, three offset values are chosen to compute four boundary toolpaths. For each boundary toolpath, a direction of right or left is implemented (e.g., right or left around the envelope). The first boundary toolpath is used to link the first and second path using the right direction and the third and last path using the left direction.

[00176] By using the opposite direction, the quantity of overlap in the same area is minimized. The second boundary toolpath is used to link the second and third paths. Finally, the third boundary toolpath starts at the end of the fourth path and goes around the part to form the net shape aspect (*see* e.g., Figure 10A and 10B).

[00177] In this manner, a toolpath is determined for generating a single continuous, uninterrupted overlapped layer within a slice. Method (300b) can be re-iterated for each horizontal slice, determined at act (306a) in Figure 3A.

[00178] In the case of interlayer continuous printing (e.g., connecting the multiple overlapped slices together) – the last boundary toolpath of each slice can also be used to join the previous and next slice together. The offset for each boundary layer is preferably implemented in a way that the maximum overlap between layers in the XY plan and in the Z direction is around 50%. In this manner, the toolpath is not just continuous within a slice, but as between multiple slices. Accordingly, the 3D part can be manufactured with a total continuous toolpath.

V. ALTERNATIVE AND SPECIFIC EMBODIMENTS

[00179] The following is a discussion of other alternative, or specific embodiments.

[00180] *(i.) Implementing Methods with Remote Computer and/or Server*

[00181] In method (300a), one or more of acts (302a) – (308a) can be performed on computer terminal (104), or otherwise, any other external server. For example, acts (302a) – (308a) can be performed on computer terminal (104), or an external server. Once the toolpath configuration is determined at act (308a), it can then be transmitted to the additive manufacturing (AM) system (102) to execute act (310a).

[00182] In other examples, acts (302a) – (308a) can be performed by any combination of the AM system (102) and the computer terminal (103) (or any other external server).

[00183] Similarly, all or any part of method (300b) can be performed by the computer terminal (104) (or an external server) and/or any combination of the computer terminal (104) (or external server), and the AM system (102).

[00184] *(ii.) Determining Direction-Specific Local Convex Subareas.*

[00185] Figures 14A and 14B provide an example technique for resolving local convex subareas, at act (310b) in Figure 3B, for a given toolpath direction (e.g., X-direction or Y-direction).

[00186] Figure 14A shows a technique for determine local convex subareas when operating the toolpath in the X-direction (e.g., zig-zags extending along the X-axis). Figure 14B shows a technique for determining local convex subareas when operating the toolpath in the Y-direction (e.g., zig-zags extending along the Y-axis).

[00187] As shown, the method can involve generating a series of rays that are casted in the toolpath direction, e.g., X-direction (Figure 14A) and Y-direction (Figure 14B), and with a spaced distance equal to the pre-defined bead thickness of the AM printer. For each ray, the number of intersections with the envelope boundary, for that horizontal layer, is computed. If the number of intersections is equal to two, then the printable area is considered convex around the casted ray.

[00188] In a case where the number of intersections is higher than two, the system identifies a pair of intersection points (1450) for that ray (FIG. 14A), separated by an area outside the printable area (550). Between each pair of intersection points (1450), an intermediate point (1402) is determined for that ray, where the intermediate point (1402) is equally distally located – along that ray – between the pair of intersection points (1450) (see dotted line along which point (1420) is disposed, between points (1450)). For intermediate points (1402) disposed along a common line orthogonal to the rays,

these points are adjoined along a common linking ray (1404), which defines a segmentation line to segment different convex subareas.

[00189] For example, as shown, all the points computed respectively in the X and Y directions are then linked together in a sequenced manner (see e.g., links (1404)). The resulting lines consequently divide the concave printable area into multiple local convex subareas.

[00190] As noted previously, the interest of dividing the concave space into multiple convex spaces is to ensure a continuous deposition into these areas and increase the number of entry points when it comes to linking all the paths together, and consequently limiting the length of the bridges linking the paths together.

[00191] To that end, while the rays in FIG. 14B are shown oriented along the X-axis, the method is applying assuming the rays are in-fact oriented along the orthogonal Y-axis.

[00192] *(iii.) Modifying Parameters and Customization.*

[00193] The goal of coding from a deep level a new slicer can focus on continuous overlapping paths, and can define enough variables and parameters to overcome future potential practical or structural struggles by giving enough freedom to modify the slicing pattern.

[00194] Common parameters such as bead height, bead thickness, number of boundary layers, percentage of infill, number of paths per slice are available. These parameters can be fixed for all the slicing processes or can be changed for every, or some, slice. These per-slice parameters can be set or modified at act (304a), in Figure 3A. Parameters focused on the overlapping pattern and the zig-zag pattern are also available.

[00195] *(iv.) Modified Overlapping Continuous Toolpath.*

[00196] In the described embodiments, a zig-zag pattern is used. In the circled areas (1302), highlighted in Figures 13A and 13B, weaker boundaries are observed in between the local convex areas, in the overlapped patterns (1300a) and (1300b) for each of the Stanford bunny and the double nut structure.

[00197] To address this problem, the zig-zag parameters can be modified such as presented in Figure 15. Figure 15 shows modified zig-zag parameters for local convex subareas for the Stanford bunny in the X-direction (1500a) and Y-direction (1500b). Also shown is the modified zig-zag parameters for the double-nut in the Y-direction (1500c).

[00198] As shown, the toolpaths presented in Figure 15 show a non-linear bounding between two convex subareas. In this example, the zig-zag patterns crosses-over between the local convex subareas. This mitigates for weakened zones (1302) (Figure 13). In turn, this generates a modified overlapping continuous toolpath having improved mechanical properties at the interfaces between the local convex subareas.

[00199] The modified overlapping toolpath is exemplified in Figure 16. Figure 16 shows the modified overlapped toolpath for a layer of the Stanford bunny (1600a), and also including the connecting boundary layers (1600b). Similarly, the modified toolpath is shown for a layer of the double nut (1600c), and also including the connecting boundary layer (1600d).

[00200] In some examples, the modified zig-zag configuration can be used for all, or some, of the horizontal slices.

[00201] *(v.) Radius of Curvature of Fiber Deposits.*

[00202] In at least on example, to consider the radius of curvature of the deposit material (e.g., carbon fiber) in the zig-zag pattern, a convolution filter was enabled to smooth the curvature of each turn. The number of paths was also be modified to increase the radius of curvature. In other words, instead of having two paths with an offset equal to twice the bead thickness, a path can be added with an offset equal to three (3) times the bead thickness and consequently increase the radius of curvature.

[00203] In some examples, curvature while changing direction is also considered using a convolution filter. For example, this can be modified at act (304a) in Figure 3A.

[00204] *(vi.) Example Method for Height Awareness Mapping.*

[00205] In at least one embodiments, for each waving pattern, a "lower slice awareness" map is generated to avoid collision between the deposition nozzle and the previously deposit matrix. This map may encode the vertical motion of the nozzle according to the average height of material deposited in its closed neighborhood.

[00206] Due to the overlap of multiple pathways within a slice, a height awareness map can be generated. This map aims to minimize the collisions between the nozzle and the material already deposited but it is also to maintain a continuous material flow along the printing.

[00207] After each slice, the height awareness map is reinitialized. The height awareness map takes as input a discretized version of the paths located below the current path for which the map is

computed and another discretized version of the current path. For each point in the current path, the nearest neighbors inside the underneath path are selected. The z value of the studied point is then modified to be far enough from any underneath neighbors. The influence of each neighbor is implemented according to the distance between the studied point and the selected neighbor.

[00208] The overhaul complexity of the sequence of algorithms for height awareness computation is $n\log(n)$ with n is the number of points on the discretized version of the path.

[00209] *(vii.) Example Implementation.*

[00210] In at least one example, the described methods (e.g., methods (300a) – (300b)) are coded using “foundation” python libraries providing elementary objects such as polygons, lines and points and useful linear algebra and geometry functions.

[00211] More generally, the sequence of algorithms is coded in Python and uses open-source libraries available under the MIT license. The sequence is implemented in a way that all the printing parameters are fully customizable. The only fixed parameters are the type of infill pattern (zigzag) and the number of axes (3 – axis 3D printing)

[00212] In some examples, the computational time for the slicing process with zig-zag infill is in the same order as open-source slicers such as Cura or Slic3r when no support is computed. The sequence of algorithms provided from a STO file, a 3-axis continuous overlapping toolpath under Gcode format. Common and specific parameters are available to control the geometry, the temperature, and the speed of the print.

VI. EXAMPLE HARDWARE CONFIGURATIONS

[00213] Reference is made to Figure 17A, which shows a simplified hardware block diagram of an example additive manufacturing system (102).

[00214] As shown, the system includes a processor (1702a) coupled, via a data bus, to a memory (1704a) and one or more of a tool face (or deposition) subsystem (1706a), communication interface (1708a), display interface (1710a) and an input interface (1712a).

[00215] In at least one embodiment, communication interface (1708a) may comprise a cellular modem and antenna for wireless transmission of data to the communications network.

[00216] Display interface (1710a) can be an output interface for displaying data (e.g., an LCD screen). Input interface (1712a) can be any interface for receiving user inputs (e.g., a keyboard, mouse, touchscreen, etc.). In some examples, the display and input interface or one of the same (e.g., in the case of a touchscreen display).

[00217] It will be understood by those of skill in the art that references herein to AM system (102) as carrying out a function or acting in a particular way imply that processor (1702a) is executing instructions (e.g., a software program) stored in memory (1704a) and possibly transmitting or receiving inputs and outputs via one or more interface.

[00218] The tool face (deposition) subsystem (1706a) comprises the deposition assembly (108), as explained above. This subsystem (1706a) is controllable to execute the printing of 3D part components in accordance with the disclosed methods.

[00219] Reference is made to Figure 17B, which shows a simplified hardware block diagram of an example computer terminal (104).

[00220] As shown, the computer terminal (104) includes a processor (1702b) coupled, via a data bus, to a memory (1704b) and one or more of a display interface (1706b), an input interface (1706b) and a communication interface (1710b). These components may have an analogous hardware architecture of the communication interface (1708a), display interface (1710a) and an input interface (1712a).

[00221] It will be understood by those of skill in the art that references herein to computer terminal (104) as carrying out a function or acting in a particular way imply that processor (1702b) is executing instructions (e.g., a software program) stored in memory (1704b) and possibly transmitting or receiving inputs and outputs via one or more interface.

[00222] If system (100) includes external servers, they may have an analogous architecture as the computer terminal (104), although they may not necessarily include an input and display interface.

VII. INTERPRETATION

[00223] Various systems or methods have been described to provide an example of an embodiment of the claimed subject matter. No embodiment described limits any claimed subject matter and any claimed subject matter may cover methods or systems that differ from those described

below. The claimed subject matter is not limited to systems or methods having all of the features of any one system or method described below or to features common to multiple or all of the apparatuses or methods described below. It is possible that a system or method described is not an embodiment that is recited in any claimed subject matter. Any subject matter disclosed in a system or method described that is not claimed in this document may be the subject matter of another protective instrument, for example, a continuing patent application, and the applicants, inventors or owners do not intend to abandon, disclaim or dedicate to the public any such subject matter by its disclosure in this document.

[00224] Furthermore, it will be appreciated that for simplicity and clarity of illustration, where considered appropriate, reference numerals may be repeated among the figures to indicate corresponding or analogous elements. In addition, numerous specific details are set forth in order to provide a thorough understanding of the embodiments described herein. However, it will be understood by those of ordinary skill in the art that the embodiments described herein may be practiced without these specific details. In other instances, well-known methods, procedures and components have not been described in detail so as not to obscure the embodiments described herein. Also, the description is not to be considered as limiting the scope of the embodiments described herein.

[00225] It should also be noted that the terms “coupled” or “coupling” as used herein can have several different meanings depending in the context in which these terms are used. For example, the terms coupled or coupling may be used to indicate that an element or device can electrically, optically, or wirelessly send data to another element or device as well as receive data from another element or device. As used herein, two or more components are said to be “coupled”, or “connected” where the parts are joined or operate together either directly or indirectly (i.e., through one or more intermediate components), so long as a link occurs. As used herein and in the claims, two or more parts are said to be “directly coupled”, or “directly connected”, where the parts are joined or operate together without intervening intermediate components.

[00226] It should be noted that terms of degree such as "substantially", "about" and "approximately" as used herein mean a reasonable amount of deviation of the modified term such that the end result is not significantly changed. These terms of degree may also be construed as including a deviation of the modified term if this deviation would not negate the meaning of the term it modifies.

[00227] Furthermore, any recitation of numerical ranges by endpoints herein includes all numbers and fractions subsumed within that range (e.g. 1 to 5 includes 1, 1.5, 2, 2.75, 3, 3.90, 4, and 5). It is also to be understood that all numbers and fractions thereof are presumed to be modified by the term "about" which means a variation of up to a certain amount of the number to which reference is being made if the end result is not significantly changed.

[00228] The example embodiments of the systems and methods described herein may be implemented as a combination of hardware or software. In some cases, the example embodiments described herein may be implemented, at least in part, by using one or more computer programs, executing on one or more programmable devices comprising at least one processing element, and a data storage element (including volatile memory, non-volatile memory, storage elements, or any combination thereof). These devices may also have at least one input device (e.g. a pushbutton keyboard, mouse, a touchscreen, and the like), and at least one output device (e.g. a display screen, a printer, a wireless radio, and the like) depending on the nature of the device.

[00229] It should also be noted that there may be some elements that are used to implement at least part of one of the embodiments described herein that may be implemented via software that is written in a high-level computer programming language such as object oriented programming or script-based programming. Accordingly, the program code may be written in Java, Swift/Objective-C, C, C++, Javascript, Python, SQL or any other suitable programming language and may comprise modules or classes, as is known to those skilled in object oriented programming. Alternatively, or in addition thereto, some of these elements implemented via software may be written in assembly language, machine language or firmware as needed. In either case, the language may be a compiled or interpreted language.

[00230] At least some of these software programs may be stored on a storage media (e.g. a computer readable medium such as, but not limited to, ROM, magnetic disk, optical disc) or a device that is readable by a general or special purpose programmable device. The software program code, when read by the programmable device, configures the programmable device to operate in a new, specific and predefined manner in order to perform at least one of the methods described herein.

[00231] Furthermore, at least some of the programs associated with the systems and methods of the embodiments described herein may be capable of being distributed in a computer program product comprising a computer readable medium that bears computer usable instructions for one or

more processors. The medium may be provided in various forms, including non-transitory forms such as, but not limited to, one or more diskettes, compact disks, tapes, chips, and magnetic and electronic storage. The computer program product may also be distributed in an over-the-air or wireless manner, using a wireless data connection.

[00232] The term "software application" or "application" refers to computer-executable instructions, particularly computer-executable instructions stored in a non-transitory medium, such as a non-volatile memory, and executed by a computer processor. The computer processor, when executing the instructions, may receive inputs and transmit outputs to any of a variety of input or output devices to which it is coupled. Software applications may include mobile applications or "apps" for use on mobile devices such as smartphones and tablets or other "smart" devices.

[00233] A software application can be, for example, a monolithic software application, built in-house by the organization and possibly running on custom hardware; a set of interconnected modular subsystems running on similar or diverse hardware; a software-as-a-service application operated remotely by a third party; third party software running on outsourced infrastructure, etc. In some cases, a software application also may be less formal, or constructed in ad hoc fashion, such as a programmable spreadsheet document that has been modified to perform computations for the organization's needs.

[00234] Software applications may be deployed to and installed on a computing device on which it is to operate. Depending on the nature of the operating system and/or platform of the computing device, an application may be deployed directly to the computing device, and/or the application may be downloaded from an application marketplace. For example, user of the user device may download the application through an app store such as the Apple App Store™ or Google™ Play™.

[00235] The present invention has been described here by way of example only, while numerous specific details are set forth herein in order to provide a thorough understanding of the exemplary embodiments described herein. However, it will be understood by those of ordinary skill in the art that these embodiments may, in some cases, be practiced without these specific details. In other instances, well-known methods, procedures and components have not been described in detail so as not to obscure the description of the embodiments. Various modification and variations may be

made to these exemplary embodiments without departing from the spirit and scope of the invention, which is limited only by the appended claims.

CLAIMS:

1. A method for manufacturing a polymer-based part using additive manufacturing comprising:

- generating a plurality of horizontally sliced layers of a virtual three-dimensional (3D) part model,

  wherein the virtual 3D part model extends along a printing axis, and the horizontally sliced layers are defined in horizontal planes orthogonal to the printing axis, and

  wherein the plurality of horizontal layers extend, along the printing axis, between a first printable layer and a last printable layer;

- for each horizontal slice, determining one or more envelope boundaries,

  wherein the envelopes define at least one printable cross-sectional area of the horizontal slice;

- for each horizontal slice, determining a slice-specific toolpath pattern,

  wherein each slice-specific toolpath pattern defines a continuous overlapped and interwoven toolpath pattern for that slice, and covering the printable area for that slice; and

- manufacturing the part by operating an additive manufacturing (AM) system according to the slice-specific toolpath pattern for each slice layer,

  wherein the 3D part model is printed, one slice at a time, from the first printable layer to the last printable layer, along the printing axis.

2. The method of claim 1, wherein the AM system is configured to print in a first and a second toolpath printing direction.

3. The method of claim 2, wherein the first and second toolpath directions are orthogonal to each other, along a horizontal slice plane.

4. The method of any one of claims 2 or 3, wherein the printing axis defines a vertical Z-axis, and the first and second toolpath directions are defined in the X- and Y-axis directions.

5. The method of any one of claims 2 to 4, wherein determining the slice-specific toolpath pattern for a given horizontal slice comprises:

- in respect of the first toolpath direction, determining a corresponding first and second continuous toolpath pattern,
  each pattern comprising a zig-zag extending along the first toolpath direction and covering the printable cross-sectional area;

- in respect of the second toolpath direction, determining a corresponding first and second continuous toolpath pattern in the second toolpath direction,
  each pattern comprising a zig-zag extending along the second toolpath direction and covering the printable cross-sectional area;

- generating an overlaid toolpath pattern, the overlaid pattern comprising a superimposed overlaying of the toolpath patterns determined for each toolpath direction,
  wherein the toolpath patterns are overlaid, over each other, in a direction of the printing axis, and
  wherein the printable areas, represented in each toolpath pattern, are orientationally aligned; and

- generating one or more connective toolpaths that link between the overlaid toolpath patterns, to generate the slice-specific toolpath pattern, defining a continuous overlapped and interwoven toolpath pattern for that slice.

6. The method of claim 5, wherein, in respect of each toolpath direction, the second continuous toolpath pattern is offset relative to the first continuous toolpath pattern,

wherein the offset is defined such that, when the second continuous toolpath pattern is overlaid, along the printing axis, over the first continuous toolpath pattern, the second pattern includes a zig-zag toolpath positioned between adjacent path lines of the first path zig-zag, when viewed along the printing axis.

7. The method of claim 6, wherein the toolpaths are overlaid, along the printing axis, in the overlaid toolpath pattern, in accordance with the following overlaid order:
   (a) the first continuous toolpath determined for the first toolpath direction;
   (b) the first continuous toolpath determined for the second toolpath direction;
   (c) the second continuous toolpath determined for the first toolpath direction; and
   (d) the second continuous toolpath determined for the second toolpath direction,

   wherein (a) defines the lower-most toolpath, and (d) defines the upper-most toolpath, along the printing axis.

8. The method of any one of claims 5 to 7, wherein for a given toolpath direction, determining the corresponding first and second continuous toolpath patterns, initially comprises:

- determining whether the at least one printable area, for the horizontal slice, is a concave or convex are, relative to the toolpath direction,

  wherein the printable area is a convex area if a continuous zig-zag toolpath is generatable, along the toolpath direction, within the printable area without any discontinuity zones, and

  wherein the printable area is a concave area if a continuous zig-zag toolpath is not generatable, along the toolpath direction, within the printable area, and

- based on the determination, determining the first and second continuous toolpath patterns.

9. The method of claim 8, wherein if the at least one printable area is determined to be concave, relative to the toolpath direction, then determining the corresponding first and second continuous toolpath patterns further comprises:

- segmenting the concave area into two or more convex subareas relative to the toolpath direction;
- for each convex subarea, determining a first and second toolpath zig-zag pattern, along the printing direction;
- determining one or more first linking paths connecting between each of the first toolpath patterns, of each convex subarea, to generate the first continuous toolpath pattern; and
- determining one or more second linking paths connecting between each of the second toolpath patterns, of each convex subarea, to generate the second continuous toolpath pattern.

10. The method of claim 9, wherein segmenting the concave area into two or more convex subareas comprises:
- superimposing a plurality of rays over the horizontal slice, each ray extending along the toolpath direction;
- in respect of each ray, determining the number of intersection points between the ray and the envelope for the horizontal layer;
- if the number of intersections is higher than two for a given ray, then in respect of that ray, identifying pairs of intersection points separated by an outside of the printable cross-sectional area;
- determining intermediate points that are equally distally spaced between each pair of intersection points; and
- linking, all intermediate points, aligned along a line orthogonal to the rays, to segment the concave area into multiple local convex subareas.

11. A system for manufacturing a polymer-based part using additive manufacturing comprising:
- a deposition assembly, of an additive manufacturing (AM) system, for extruding filament material to manufacture a 3D part component; and
- at least one processor coupled to the deposition assembly, and configured for:
    - generating a plurality of horizontally sliced layers of a virtual three-dimensional (3D) part model,

wherein the virtual 3D part model extends along a printing axis, and the horizontally sliced layers are defined in horizontal planes orthogonal to the printing axis, and

wherein the plurality of horizontal layers extend, along the printing axis, between a first printable layer and a last printable layer;

- for each horizontal slice, determining one or more envelope boundaries,

  wherein the envelopes define at least one printable cross-sectional area of the horizontal slice;

- for each horizontal slice, determining a slice-specific toolpath pattern,

  wherein each slice-specific toolpath pattern defines a continuous overlapped and interwoven toolpath pattern for that slice, and covering the printable area for that slice; and

- operate to the tool face subsystem to manufacture the part according to the slice-specific toolpath pattern for each slice layer,

  wherein the 3D part model is printed, one slice at a time, from the bottom-most layer to the upper-most layer, along the printing axis.

12. The system of claim 11, wherein the AM system is configured to print in a first and a second toolpath printing direction.

13. The system of claim 12, wherein the first and second toolpath directions are orthogonal to each other, along a horizontal slice plane.

14. The system of any one of claims 12 or 13, wherein the printing axis defines a vertical Z-axis, and the first and second toolpath directions are defined in the X- and Y-axis directions.

15. The system of any one of claims 12 to 14, wherein determining the slice-specific toolpath pattern for a given horizontal slice comprises the at least one processor being further configured for:

- in respect of the first toolpath direction, determining a corresponding first and second continuous toolpath pattern,

  each pattern comprising a zig-zag extending along the first toolpath direction and covering the printable cross-sectional area;

- in respect of the second toolpath direction, determining a corresponding first and second continuous toolpath pattern in the second toolpath direction,

  each pattern comprising a zig-zag extending along the second toolpath direction and covering the printable cross-sectional area;

- generating an overlaid toolpath pattern, the overlaid pattern comprising a superimposed overlaying of the toolpath patterns determined for each toolpath direction,

  wherein the toolpath patterns are overlaid, over each other, in a direction of the printing axis, and

  wherein the printable areas, represented in each toolpath pattern, are orientationally aligned; and

- generating one or more connective toolpaths that link between the overlaid toolpath patterns, to generate the slice-specific toolpath pattern, defining a continuous overlapped and interwoven toolpath pattern for that slice.

16. The system of claim 15, wherein, in respect of each toolpath direction, the second continuous toolpath pattern is offset relative to the first continuous toolpath pattern,

wherein the offset is defined such that, when the second continuous toolpath pattern is overlaid, along the printing axis, over the first continuous toolpath pattern, the second pattern includes a zig-zag toolpath positioned between adjacent path lines of the first path zig-zag, when viewed along the printing axis.

17. The system of claim 16, wherein the toolpaths are overlaid, along the printing axis, in the overlaid toolpath pattern, in accordance with the following overlaid order:
   (a) the first continuous toolpath determined for the first toolpath direction;
   (b) the first continuous toolpath determined for the second toolpath direction;
   (c) the second continuous toolpath determined for the first toolpath direction; and
   (d) the second continuous toolpath determined for the second toolpath direction,

   wherein (a) defines the lower-most toolpath, and (d) defines the upper-most toolpath, along the printing axis.

18. The system of any one of claims 15 to 17, wherein for a given toolpath direction, determining the corresponding first and second continuous toolpath patterns, initially comprises the at least one processor being further configured for:

- determining whether the at least one printable area, for the horizontal slice, is a concave or convex are, relative to the toolpath direction,

  wherein the printable area is a convex area if a continuous zig-zag toolpath is generatable, along the toolpath direction, within the printable area without any discontinuity zones, and

  wherein the printable area is a concave area if a continuous zig-zag toolpath is not generatable, along the toolpath direction, within the printable area, and

- based on the determination, determining the first and second continuous toolpath patterns.

19. The system of claim 18, wherein if the at least one printable area is determined to be concave, relative to the toolpath direction, then determining the corresponding first and second continuous toolpath patterns further comprises the at least one processor being further configured for:

- segmenting the concave area into two or more convex subareas relative to the toolpath direction;
- for each convex subarea, determining a first and second toolpath zig-zag pattern, along the printing direction;
- determining one or more first linking paths connecting between each of the first toolpath patterns, of each convex subarea, to generate the first continuous toolpath pattern; and
- determining one or more second linking paths connecting between each of the second toolpath patterns, of each convex subarea, to generate the second continuous toolpath pattern.

20. The system of claim 19, wherein segmenting the concave area into two or more convex subareas comprises the at least one processor being further configured for:
- superimposing a plurality of rays over the horizontal slice, each ray extending along the toolpath direction;
- in respect of each ray, determining the number of intersection points between the ray and the envelope for the horizontal layer;
- if the number of intersections is higher than two for a given ray, then in respect of that ray, identifying pairs of intersection points separated by an outside of the printable cross-sectional area;
- determining intermediate points that are equally distally spaced between each pair of intersection points; and
- linking, all intermediate points, aligned along a line orthogonal to the rays, to segment the concave area into multiple local convex subareas.

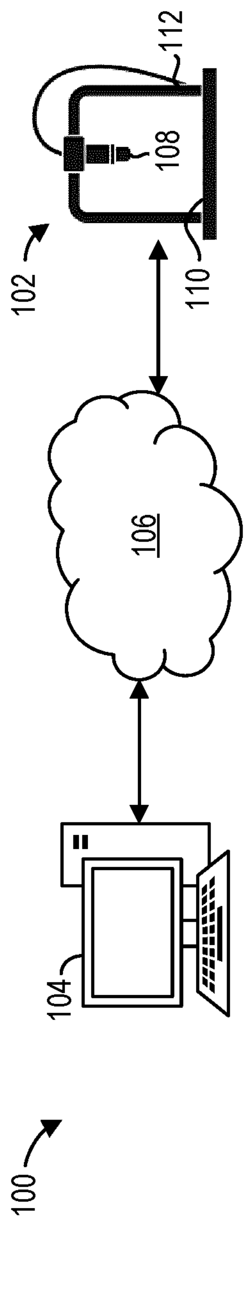

FIG. 1

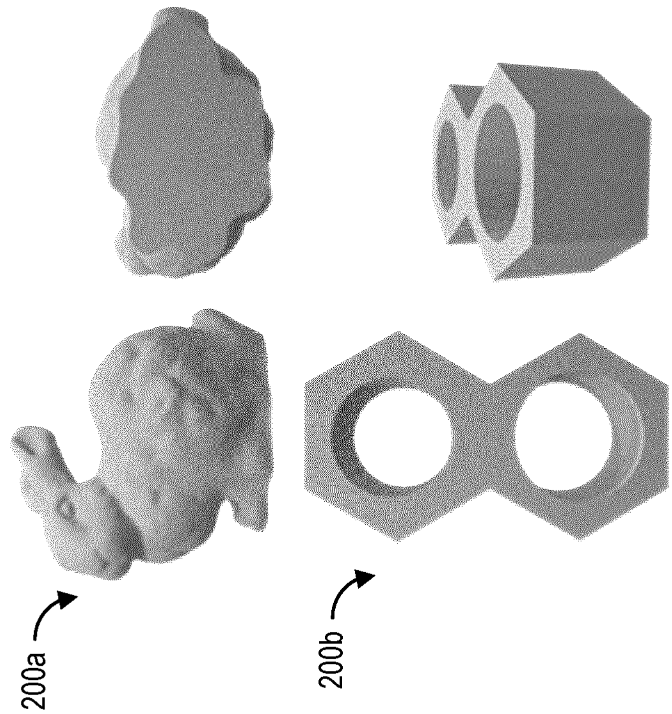

FIG. 2

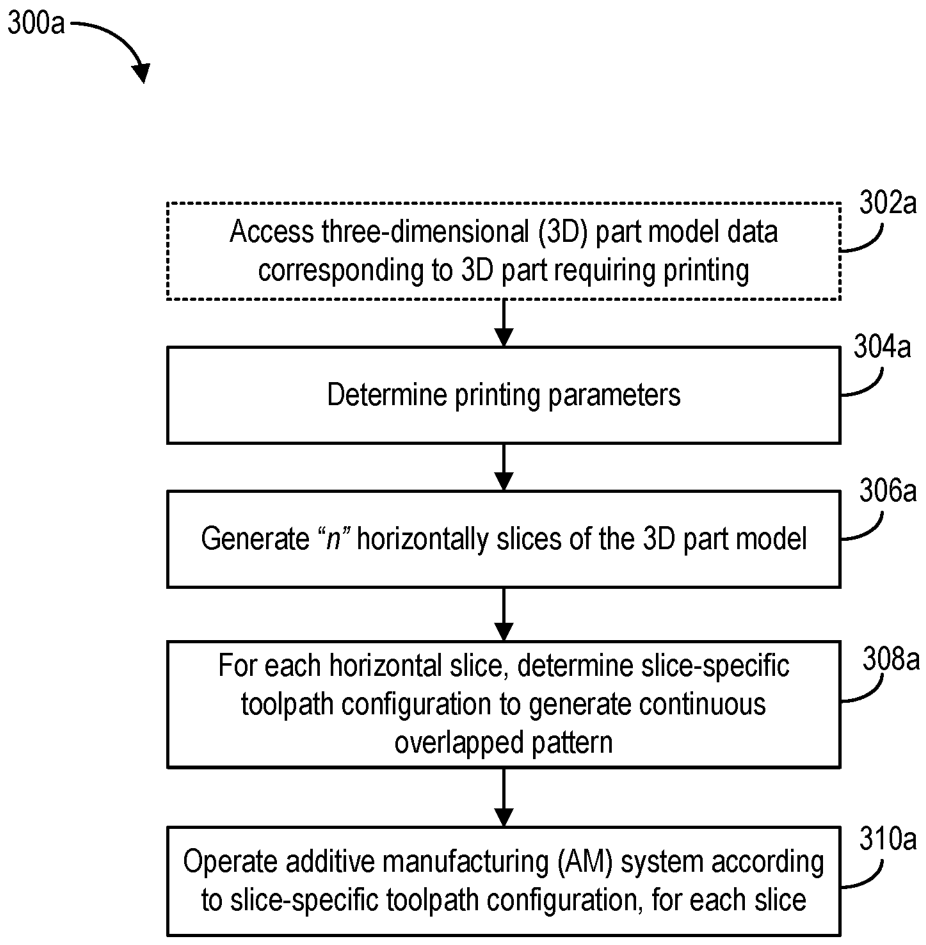
300a
302a
Access three-dimensional (3D) part model data corresponding to 3D part requiring printing
304a
Determine printing parameters
306a
Generate "n" horizontally slices of the 3D part model
308a
For each horizontal slice, determine slice-specific toolpath configuration to generate continuous overlapped pattern
310a
Operate additive manufacturing (AM) system according to slice-specific toolpath configuration, for each slice

FIG. 3A

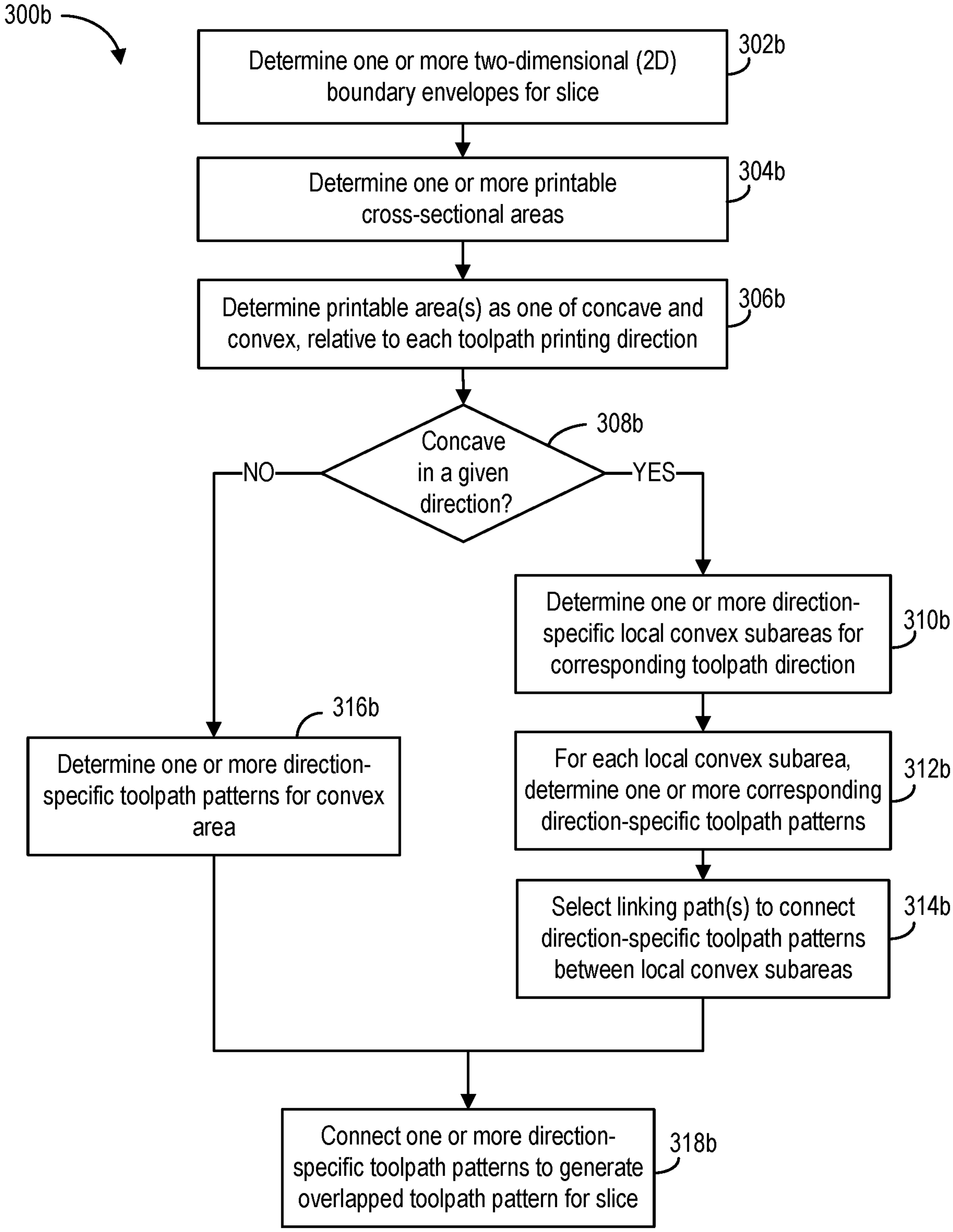
300b
Determine one or more two-dimensional (2D) boundary envelopes for slice
302b
Determine one or more printable cross-sectional areas
304b
Determine printable area(s) as one of concave and convex, relative to each toolpath printing direction
306b
Concave in a given direction?
308b
NO
YES
Determine one or more direction-specific local convex subareas for corresponding toolpath direction
310b
316b
Determine one or more direction-specific toolpath patterns for convex area
For each local convex subarea, determine one or more corresponding direction-specific toolpath patterns
312b
Select linking path(s) to connect direction-specific toolpath patterns between local convex subareas
314b
Connect one or more direction-specific toolpath patterns to generate overlapped toolpath pattern for slice
318b

FIG. 3B

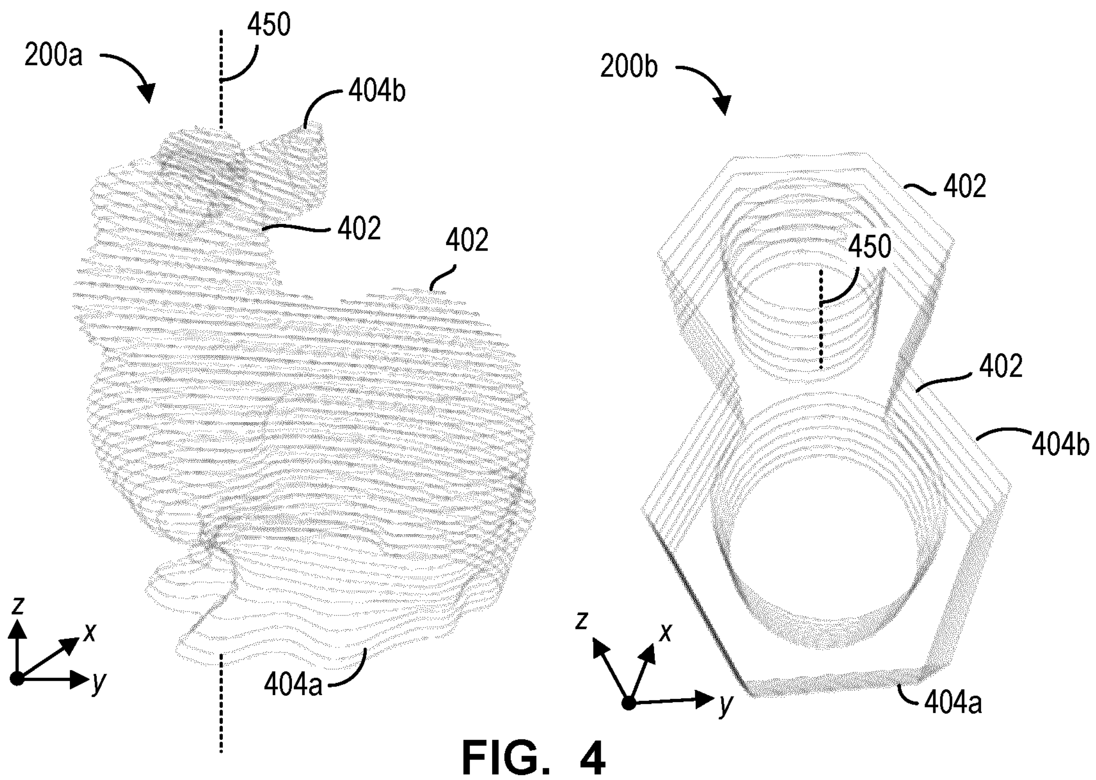
200a
450
404b
402
402
z
x
y
404a
200b
402
450
402
404b
z
x
y
404a

FIG. 4

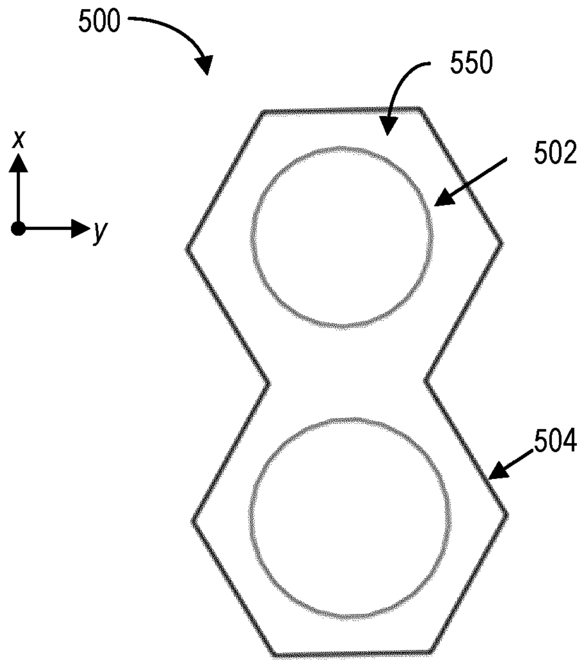
500
550
502
x
y
504

FIG. 5

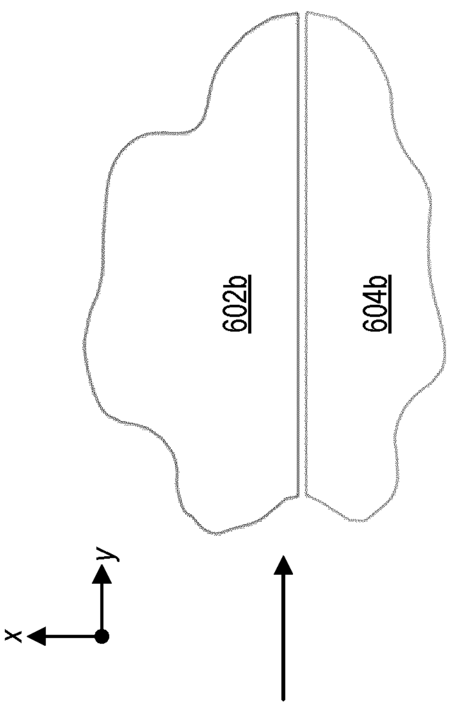

FIG. 6B

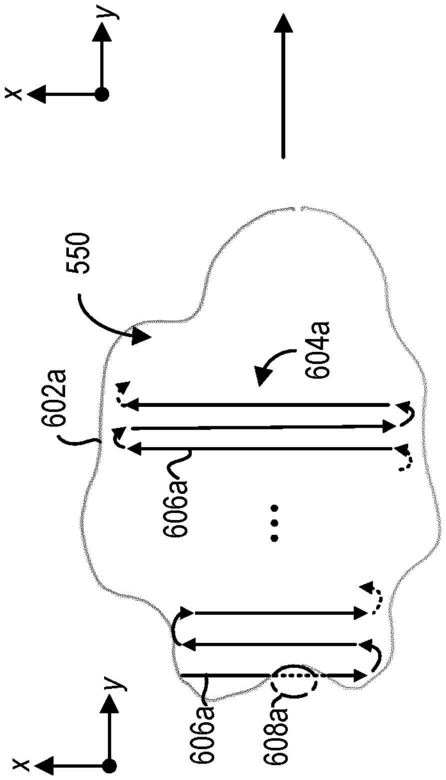

FIG. 6A

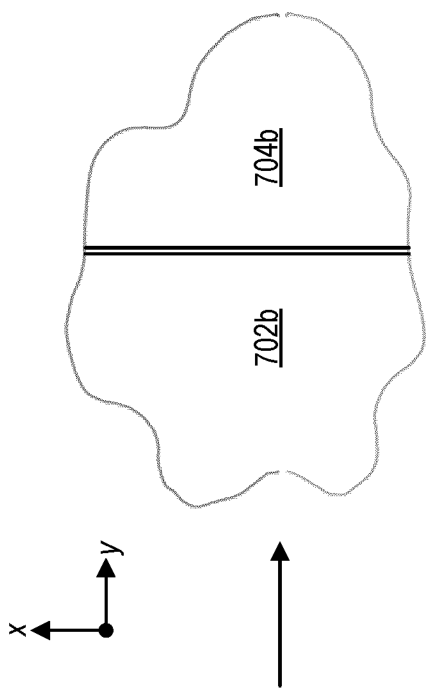

FIG. 7B

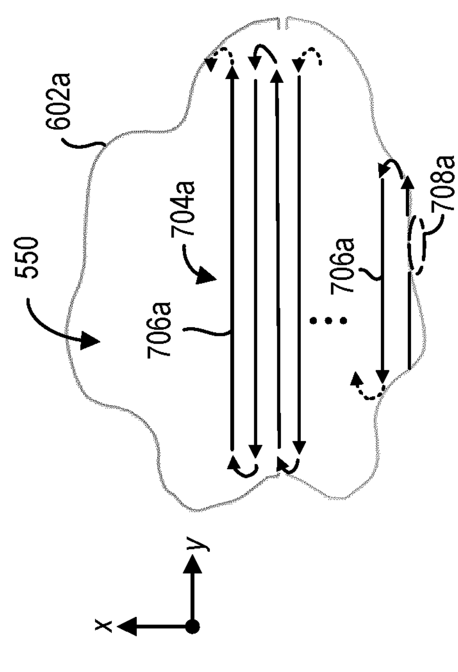

FIG. 7A

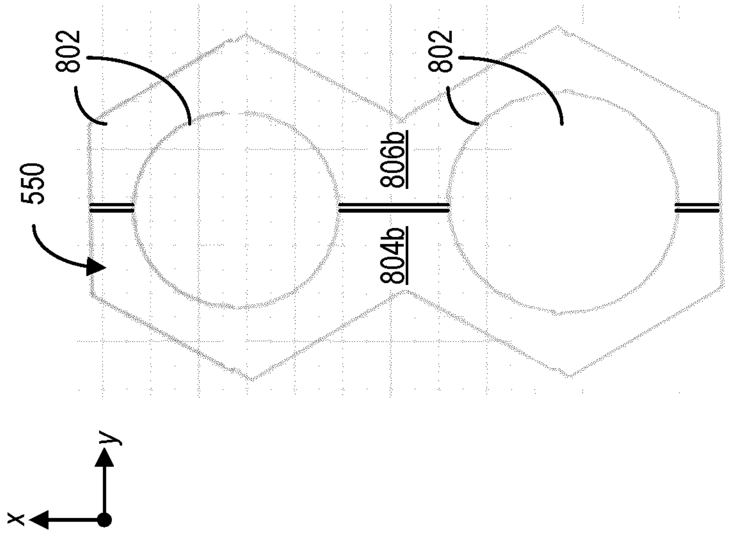

FIG. 8B

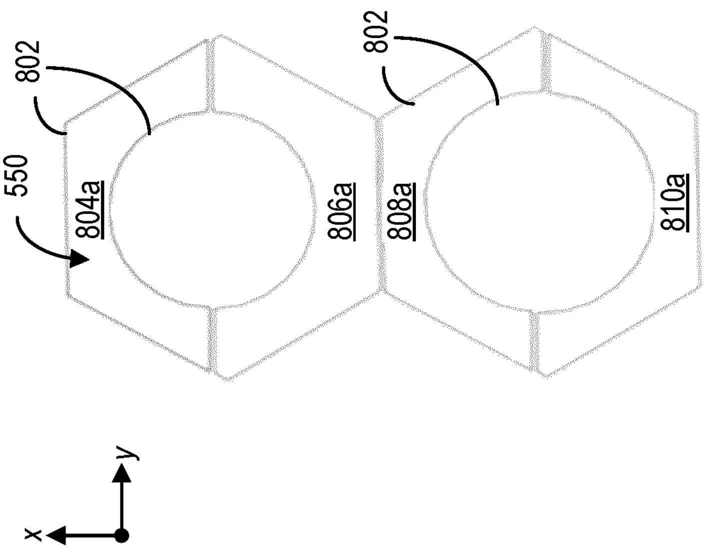

FIG. 8A

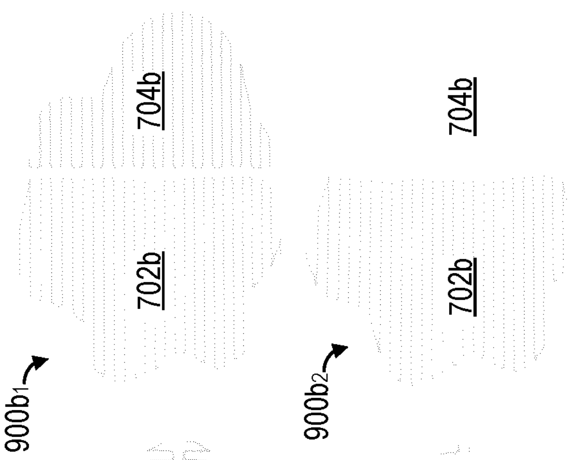

FIG. 9B

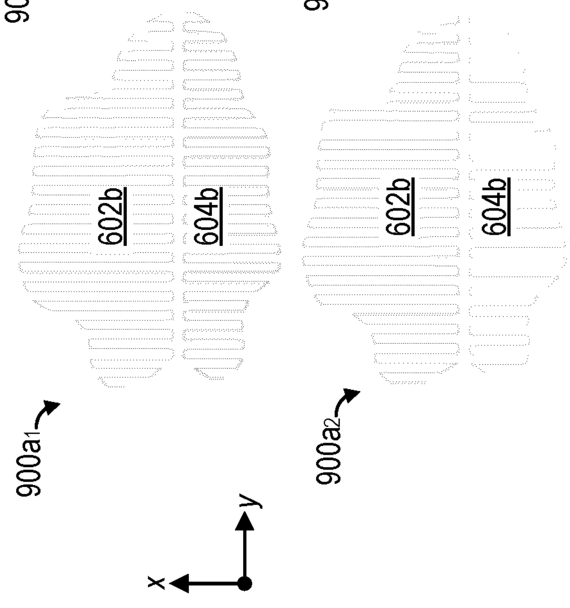

FIG. 9A

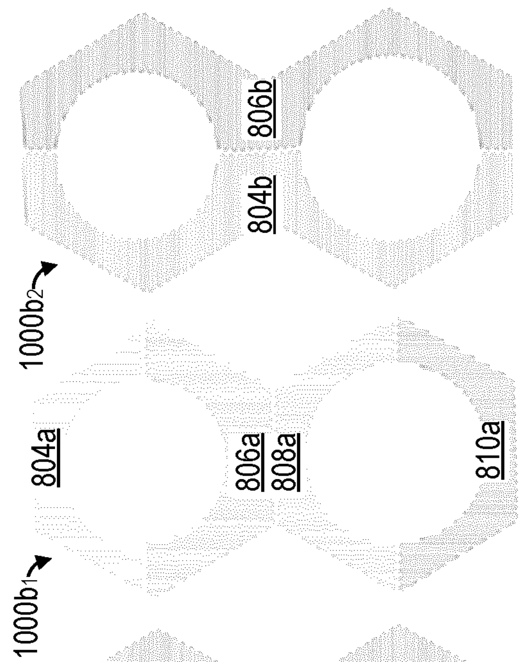

FIG. 10B

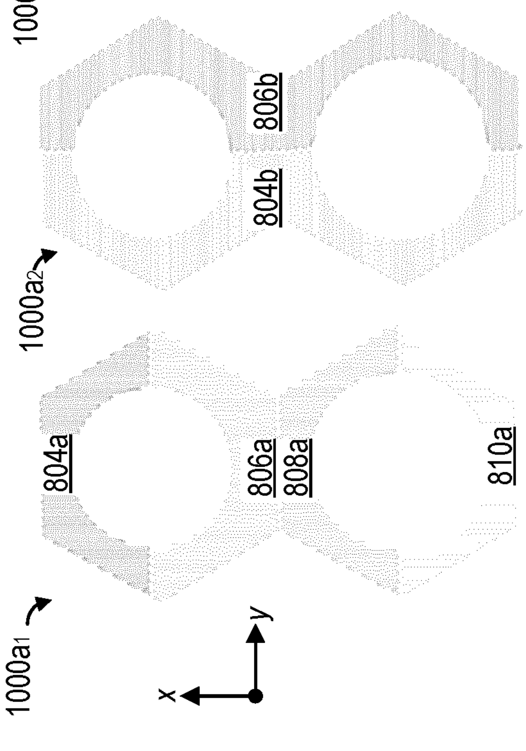

FIG. 10A

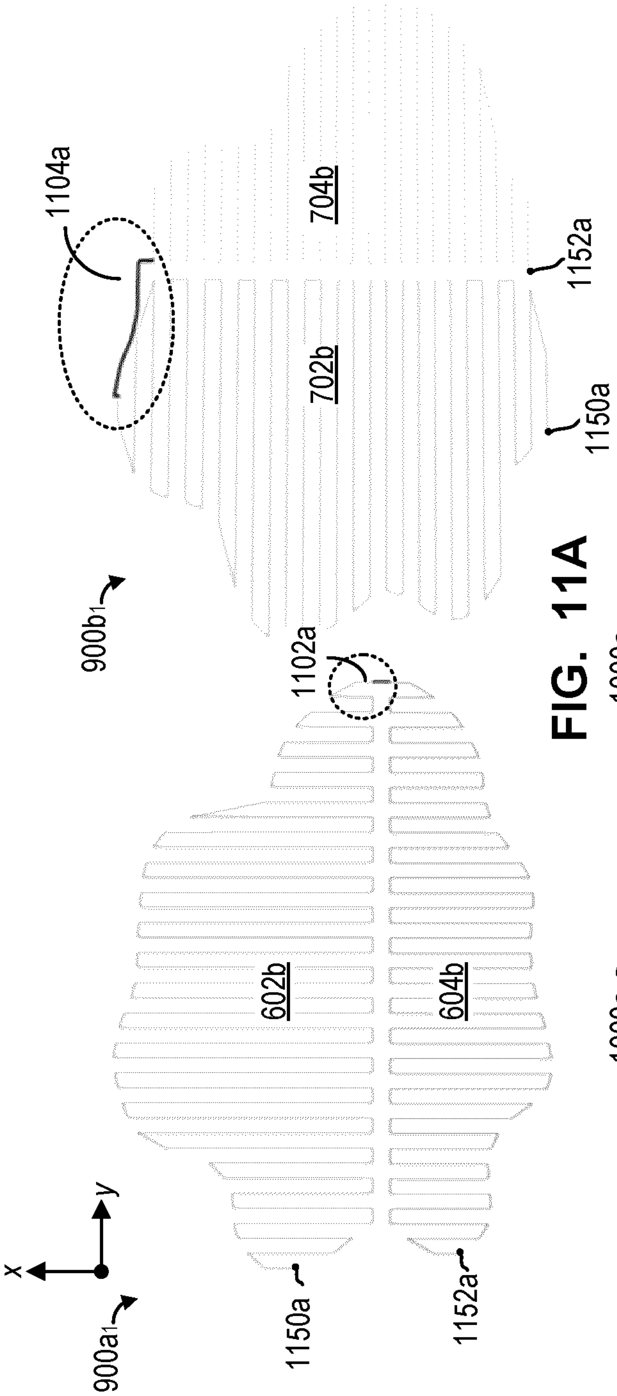

FIG. 11A

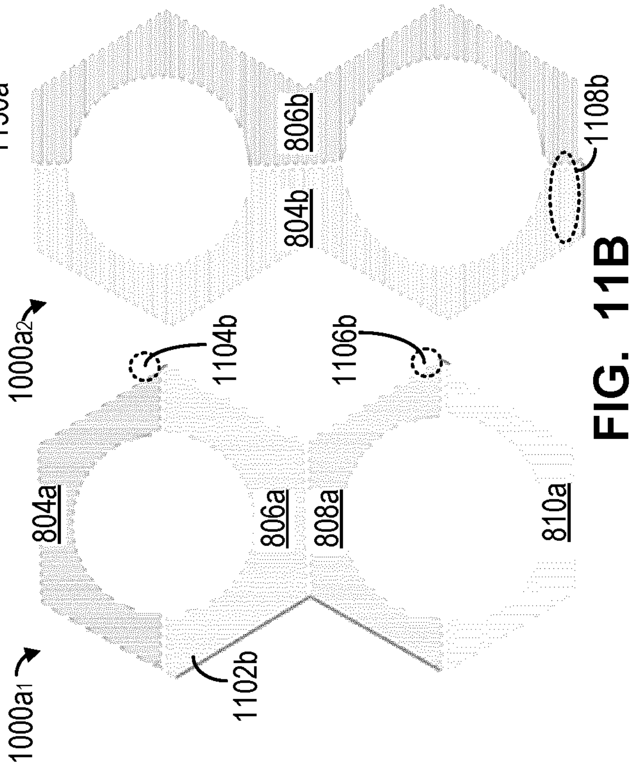

FIG. 11B

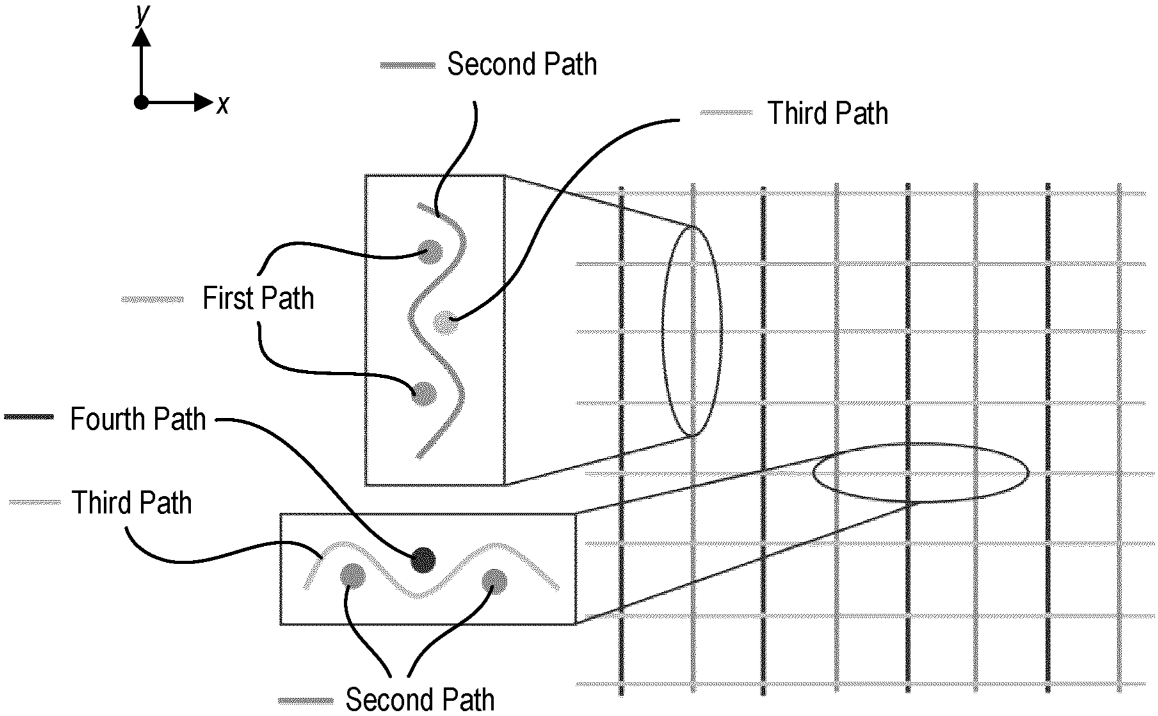

FIG. 11C

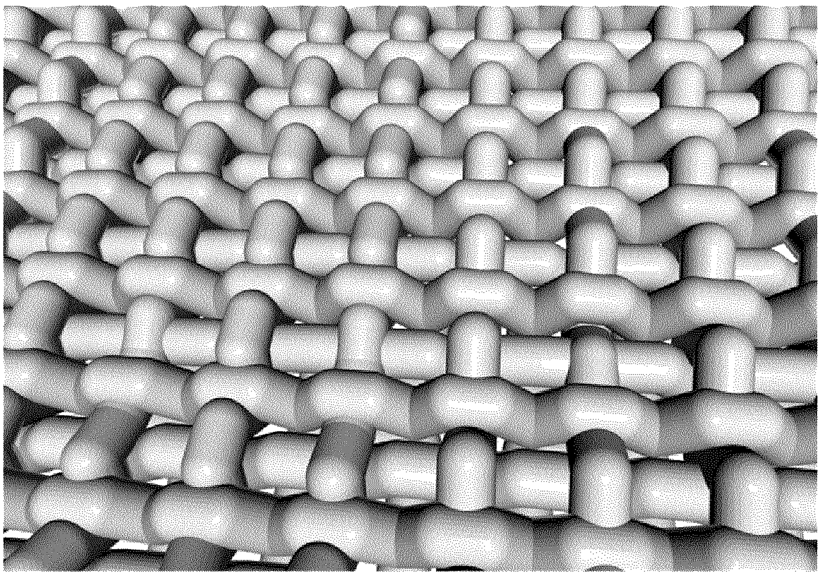

FIG. 11D

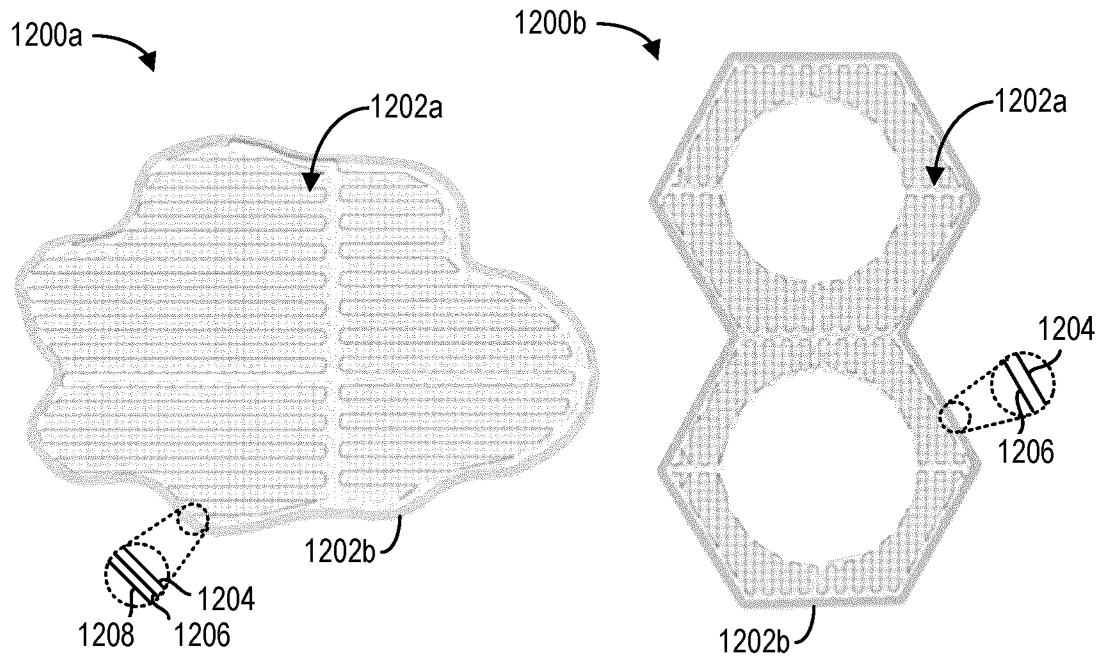
1200a
1202a
1208
1204
1206
1202b
1200b
1202a
1204
1206
1202b

FIG. 12

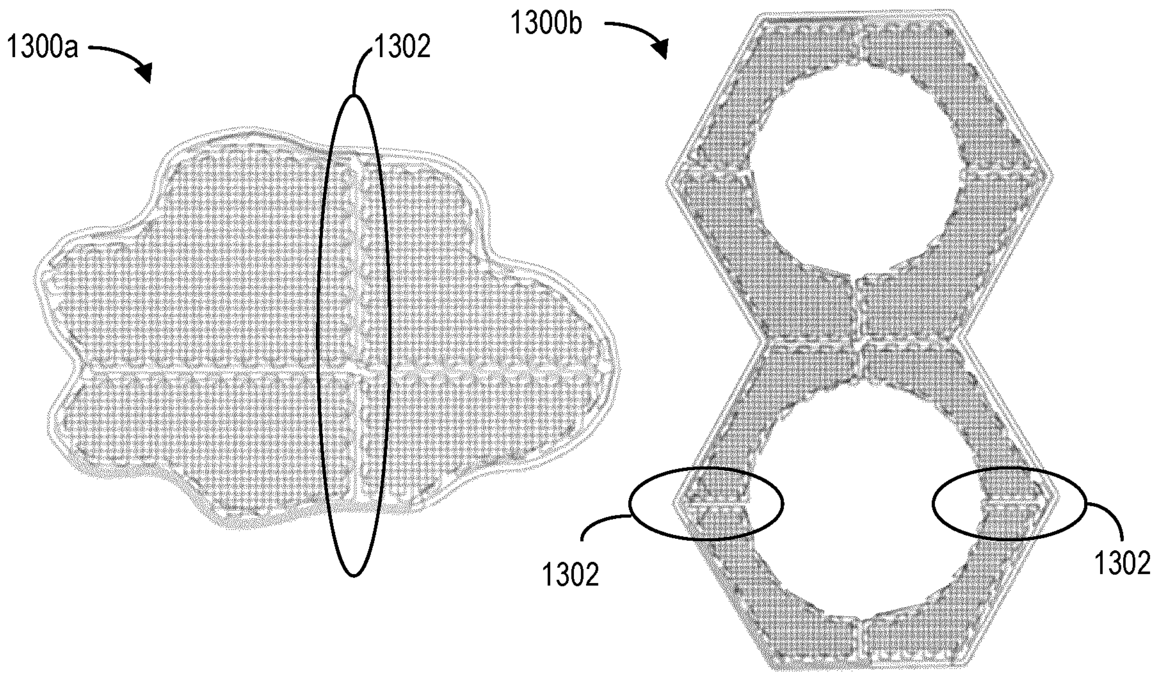
1300a
1302
1300b
1302
1302

FIG. 13

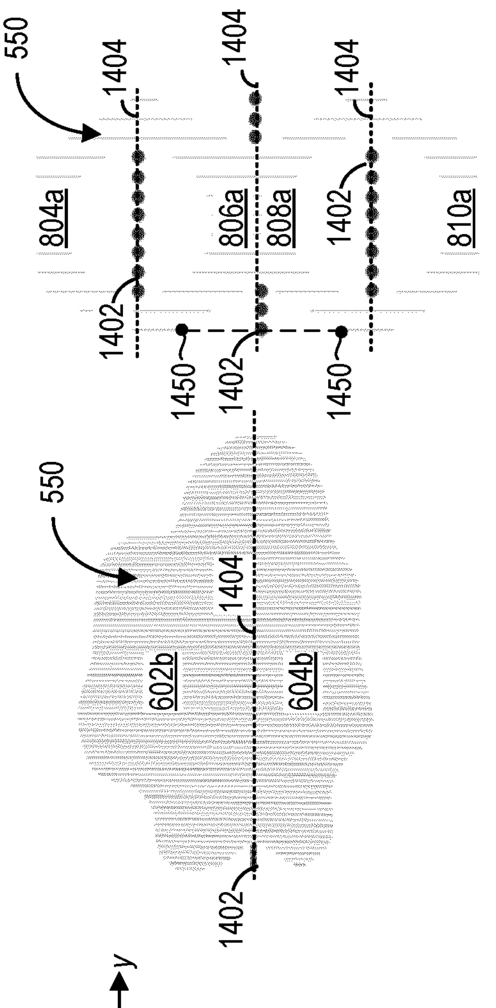

FIG. 14A

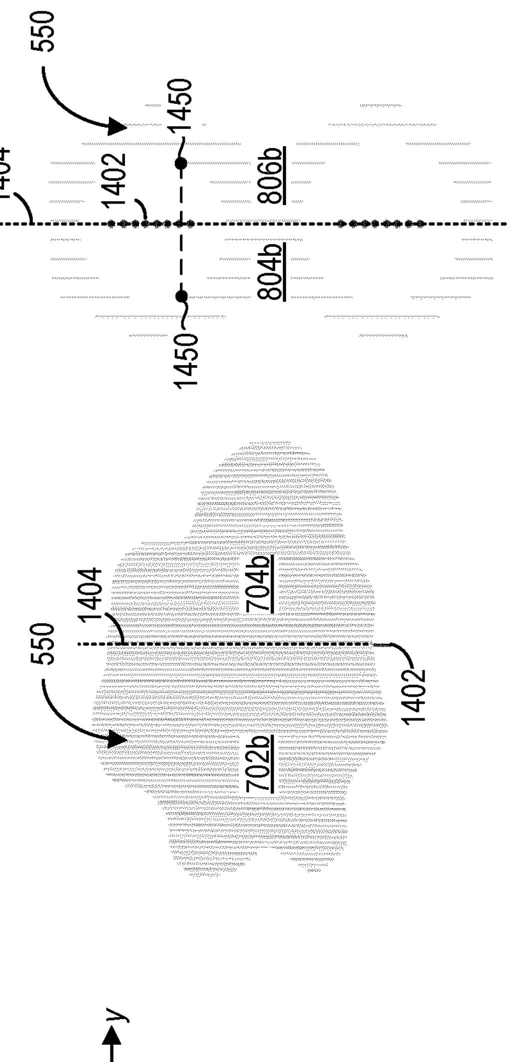

FIG. 14B

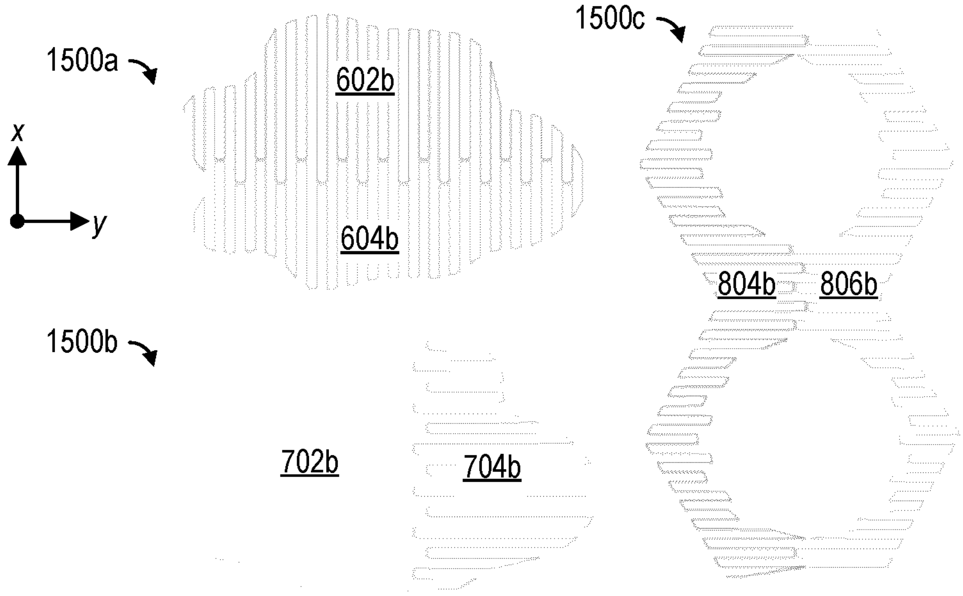
1500a
1500b
1500c
x
y
602b
604b
702b
704b
804b
806b

FIG. 15

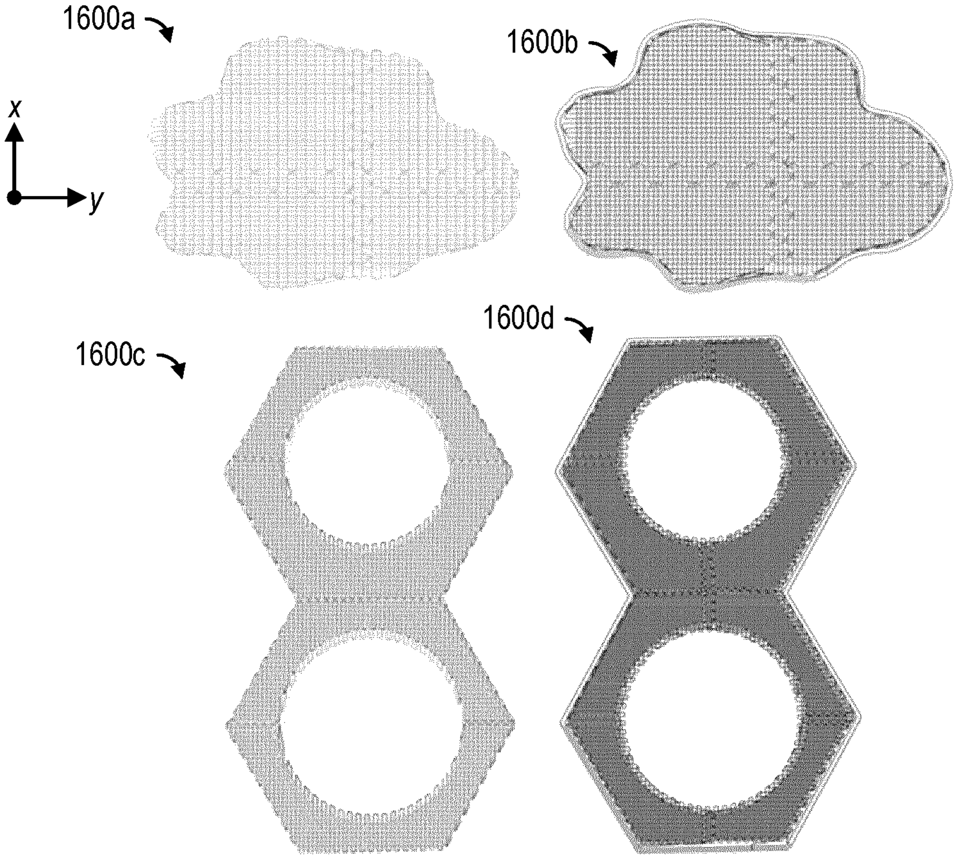
1600a
1600b
1600c
1600d
x
y

FIG. 16

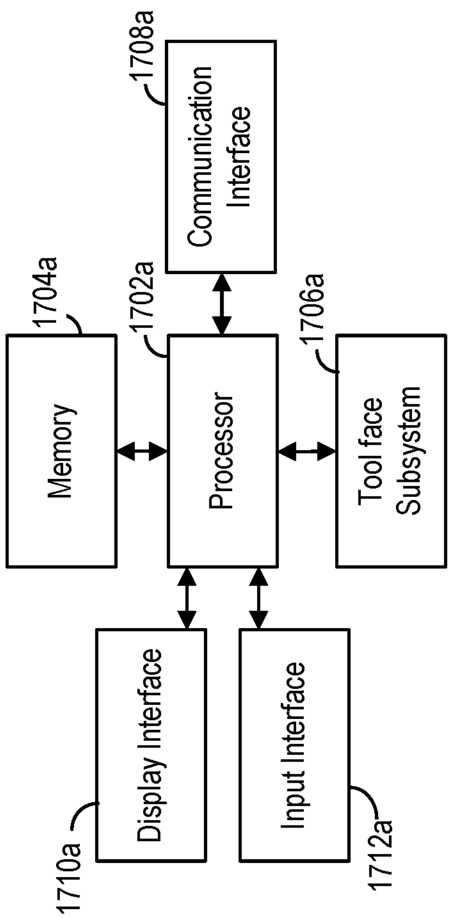

FIG. 17A

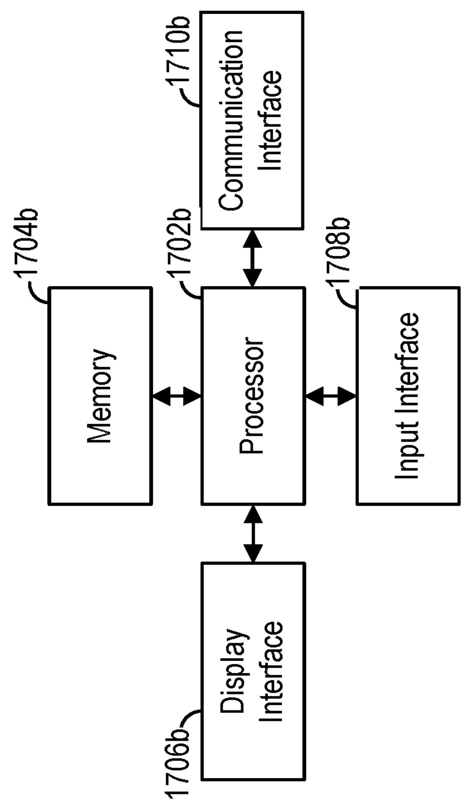

FIG. 17B

INTERNATIONAL SEARCH REPORT	International application No. **PCT/CA2023/051678**

A. CLASSIFICATION OF SUBJECT MATTER

IPC: ***B29C 64/118*** (2017.01) , ***B33Y 10/00*** (2015.01) , ***B33Y 30/00*** (2015.01) , ***B33Y 50/02*** (2015.01)

CPC: , B29C 64/118 (2021.08) , B33Y 10/00 (2020.01) , B33Y 30/00 (2020.01) , B33Y 50/02 (2020.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC: ***B29C*** (2017.01) , ***B33Y*** (2015.01)
CPC: B29C (2021.08) , B33Y (2020.01)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic database(s) consulted during the international search (name of database(s) and, where practicable, search terms used)

Questel-Orbit (Fampat) with key words, such as: additive, manufacturing, three-dimensional, 3D, virtual, CAD, computer, model, slice, horizotal, layer, processor, cpu, computer and control*.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	WO 2022/066980 A2 (FEINBERG, A. W. et al.) 31 March 2022 (31-03-2022) *fig. 12; abstract; paras. 0118-0130*	1-20
	WO 2018/127274 A1 (EDVINSSON, J.) 12 July 2018 (12-07-2018) *claim 1; figs. 1a-3; paras.0038-0047*	1-20
	US 2018/0215094 A1 (BIRNBAUM, A. J. et al.) 02 August 2018 (02-08-2022) *whole document*	1-20

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"D"	document cited by the applicant in the international application	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"E"	earlier application or patent but published on or after the international filing date	"&"	document member of the same patent family
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)		
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search	Date of mailing of the international search report
07 March 2024 (07-03-2024)	07 March 2024 (07-03-2024)

Name and mailing address of the ISA/CA	Authorized officer
Canadian Intellectual Property Office Place du Portage I, C114 - 1st Floor, Box PCT 50 Victoria Street Gatineau, Quebec K1A 0C9 Facsimile No.: 819-953-2476	Pengfei Zhang (819) 639-7928

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/CA2023/051678

Patent Document Cited in Search Report	Publication Date	Patent Family Member(s)	Publication Date
WO 2022/066980 A2	31 March 2022 (31-03-2022)	WO2022066980A2	31 March 2022 (31-03-2022)
		WO2022066980A3	05 May 2022 (05-05-2022)
		WO2022066980A8	16 March 2023 (16-03-2023)
		US2023356472A1	09 November 2023 (09-11-2023)
WO 2018/127274 A1	12 July 2018 (12-07-2018)	WO2018127274A1	12 July 2018 (12-07-2018)
		EP3565714A1	13 November 2019 (13-11-2019)
		EP3565714B1	21 October 2020 (21-10-2020)
		ES2843106T3	15 July 2021 (15-07-2021)
		PL3565714T3	17 May 2021 (17-05-2021)
		WO2018127429A1	12 July 2018 (12-07-2018)
US 2018/0215094 A1	02 August 2018 (02-08-2018)	US2018215094A1	02 August 2018 (02-08-2018)
		US10639847B2	05 May 2020 (05-05-2020)
		CA3051259A1	02 August 2018 (02-08-2018)
		EP3573815A1	04 December 2019 (04-12-2019)
		EP3573815A4	02 September 2020 (02-09-2020)
		JP2020505256A	20 February 2020 (20-02-2020)
		WO2018140382A1	02 August 2018 (02-08-2018)