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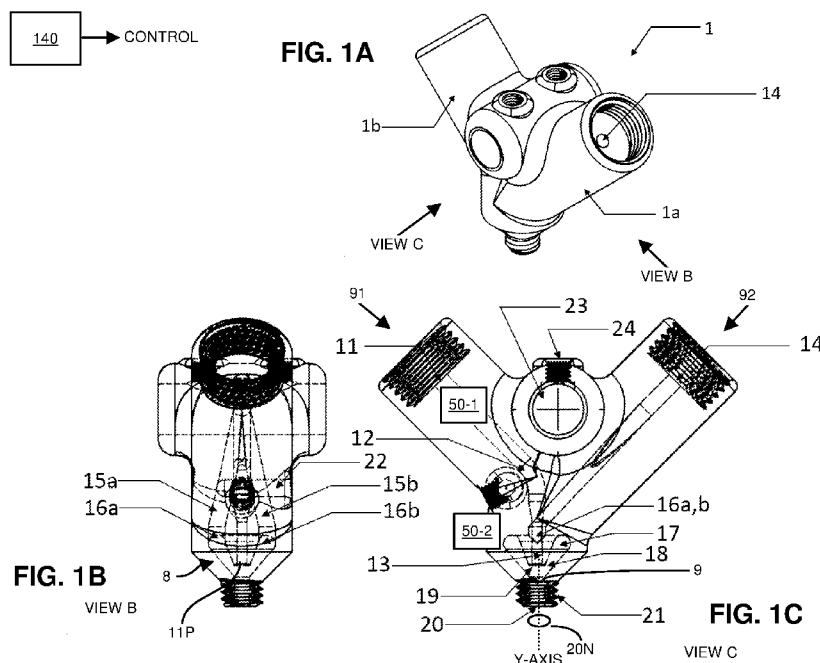
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(57) Abstract: Hot end assemblies are described including: i) two or more conduits for receiving materials, ii) one or more spiral flow channels connecting to said conduits, and iii) provisions for combining for the two or more received materials. Inventive embodiments are provided for production of coaxial coextrudates, mixing of material blends, and programming the internal geometry of one or more materials. Methods of use are disclosed to vary the composition of materials in the extrudate during use. Exemplary extruded products resulting from use are also provided and claimed.

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3D PRINTING BY COMBINING AND EXTRUSION OF MULTIPLE MATERIALS

RELATED APPLICATIONS

15 This application claims priority to earlier filed United States Patent Application Serial Number 62/982,347 entitled "FUSED DEPOSITION OF MATERIALS," Attorney Docket No. UML2020-021-00p, filed on February 27, 2020, the entire teachings of which are incorporated herein by this reference.

20 BACKGROUND

Conventional 3-D (three-dimensional) printers have been used to fabricate different types of objects.

BRIEF DESCRIPTION OF EMBODIMENTS

Embodiments herein pertain to a type of fused filament fabrication (FFF process), also referred to as fused deposition modeling (FDM), material extrusion, material extrusion additive manufacturing, and other terms. Generally, these technologies decompose a part's three-dimensional (3D) geometry into a series of printed roads that are consecutively printed to reproduce the part's 3D geometry.

Herein, the word "part" means the product being produced by the 3D printing process type of additive manufacturing. The part or product may be a device or article for sale, a component that is assembled or finished, or more generally a form of matter having a defined geometry.

In one embodiment, referred to for convenience as fused deposition modeling
35 of multiple materials (FD3M), is directed to providing in-line coextrusion of the

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deposited roads wherein the cross-sections of the roads are comprised of different materials. Examples of parts made the process may include, for example, conductive wires for electrical circuits or hollow flexible tubes for pneumatic actuators or recycled content within virgin material, among others. A second objective is to use a
5 mixing section to provide dynamic blending of multiple materials. For example, materials may be blended to vary electrical, mechanical, optical or other properties, thereby allowing gradients in the part properties that would otherwise require the development and discrete deposition of multiple grades of materials. A third object of the invention is to provide for faster switching and improved between materials with
10 improved bond integrity than is common when printing with multiple materials through separate nozzles.

The objective of a FD3M system is to provide a process for higher speed three-dimensional printing (3DP) of higher performance, higher quality products. The objective is enabled through the use of a hot end having multiple inlet ports disposed
15 at different axial, radial, and angular positions, such that varying materials may be admitted to one or more internal flow channels within the hot end and downstream nozzle.

The coextrusion of the shell around one or more inner core layers is facilitated by providing a predominately axisymmetric flow at the junction of the inner and outer
20 material flows. While reasonably axisymmetric flow can be accomplished by using a flow distributor comprised of a flow distributor that bifurcates and recombines the flows in the vicinity of the junction (flow combiner) of the inner and outer material flows, a preferred method uses distributor geometries with integrated helical or spiral flow channels of varying pitch and flow channel depth. In one embodiment, the flow
25 distributor is comprised of a generally cylindrical or conical core located within a generally cylindrical or conical cavity within the 3D printer's hot end body wherein the depth of the spiral flow channels decreases in the direction of flow of the material being processed. In some embodiments, the core and cavity of the flow distributor are integrated into a single body component while in other embodiments the core and
30 cavity of the flow distributor are comprised of different body components that are assembled. In yet other embodiments, the materials being processed are all admitted

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near the start of the flow distributor, and mixing elements are provided within the flow distributor's channels to cause blending or mixing of two or more materials.

In a first embodiment, referred to as "Unity", the hot end is comprised of a single body component with two material inputs and a flow distributor comprised of an annular flow channels fed by two drops connecting the inlet for the outer material.

In a second embodiment, referred to as "Duality Coex", the hot end is comprised of a single body component with two material inputs and a flow distributor for the outer material comprised of a spiral flow channel converging to a thin gap at the junction of the inner and outer materials.

In a third embodiment, referred to as "Duality Mixer", the hot end is comprised of a single body component with two material inputs fed to the start of a spiral flow channel with internal mixing pins converging to the inlet of a dispensing nozzle.

In a fourth embodiment, referred to as "Duality v3", the hot end is comprised of two body components with two material inputs and a flow distributor for the outer material comprised of a spiral flow channel converging to a thin gap at the junction of the inner and outer materials.

In a fifth embodiment, referred to as "Triplex", the hot end is comprised of three body components forming two flow distributors for the two outer materials, wherein each flow distributor is comprised of a spiral flow channel converging to a thin gap at the junction of the inner and outer materials.

In a sixth embodiment, referred to as "Quintet", the hot end is comprised of two body components with a flow distributor for receiving, mixing, and dispensing five materials.

In a seventh embodiment, referred to as "Compact", the hot end is comprised of three body components with two material inputs and a flow distributor formed between the surfaces of the main body and a mating nozzle that is secured by a retaining plate. Two variants of the embodiment are described including bifurcating and spiral flow distributors.

In an eighth embodiment, a method for planning and 3D printing of multiple materials as an extension of a traditional workflow is described.

In the preceding and foregoing descriptions, the term “body component” refers to the material or materials constituting the actual body of the hot end and not components connecting thereto. In other words, components such as sensors, heaters, coupling nuts, and washers are not considered “body components” (unless they are
5 solidly integrated with other body components) even though they may be assembled to form a hot end.

Similarly, the materials being processed through the flow channels in the various embodiments may be varied in their composition including, for example, polymers, metals, air or other gasses and fluids, and others including composites
10 thereof. The materials being processed will simply be referred to as “flowable materials”. It is understood that the materials will flow from a high pressure source (typically consisting of an extruder, syringe pump, or other delivery system) connected to the inlets of the hot end.

In these and yet further embodiments, the printer assembly as described herein
15 may include one or more heaters controlled in response to one or more temperature sensors. One or more heaters may be disposed to heat the corresponding sections of the hot end containing flowable materials. In some cases, the hot end may be designed to provide thermal isolation between the different sections of the hot end to achieve different temperature distributions. In cases such as the “Duality Coex” and “Duality
20 v3”, the heaters can be independently controlled with respect to each other. For example, the 3-D printer assembly includes: a first temperature sensor operable to monitor a temperature associated with the first conduit, and ii) a second temperature sensor operable to monitor a temperature associated with the second conduit. A controller controls the temperature associated with the first conduit independent of
25 controlling the temperature associated with the second conduit. It is understood that some of the designs, such as “Compact”, are not shown to include independent temperature control of the materials but may be readily modified in view of the provided embodiments that provide such independent control.

In accordance with still further embodiments, the flow of the first flowable
30 material through the core is independently controllable with respect to flow of the second or more flowable materials through the shell layers. As such, the relative proportion of two or more materials being extruded can be independently controlled.

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The concept applies to all the provided embodiments including the hot ends with mixing sections such as the “Duality Mixer” and “Quintet” so that different material blends may be produced. It is understood that the proportion of the flow of any of the flowable materials may be varied continuously from 0 to 100% so that a substantially
5 homogenous output of any of the flowable materials may be dispensed.

In yet further embodiments, the 3-D printer assembly includes a controller operable to position the hot end and thus the output flow of the dispensed material(s). The rate of flow of each of the flowable materials is independently controlled such that the proportion of the inner and outer materials may be dynamically varied along
10 with the total volumetric flow rate. Accordingly, the print speed, height, width, and composition of the extruded material is readily varied.

Further embodiments herein include a printer assembly comprising: a first conduit operative to deliver a first flowable material through a respective port of the
15 first conduit into a junction of the printer assembly; a second conduit operative to deliver a second flowable material into a flow distributor of the printer assembly, the flow distributor comprising a flow channel to deliver the second flowable material into a gap surrounding the junction; and an outlet of the printer assembly operative to dispense a combination of the first flowable material and the second flowable
20 material.

In further example embodiments, the gap of the printer assembly is a circumferential gap substantially surrounding the junction to envelope the first flowable material with the second flowable material as the first flowable material and the second flowable material pass through the junction.

25 In yet further example embodiments, the printer assembly includes: a controller operative to control, over time: i) the flow rate of the first flowable material from the first conduit, and ii) the flow rate of the second flowable material from the second conduit.

In further example embodiments, the first conduit of the printer assembly
30 provides flow of the first flowable material in a first axial direction; the flow distributor directs a flow of the second flowable material in multiple directions, which are different from the first axial direction. In one embodiment, the outlet of the

junction in the printer assembly extends to a nozzle of the printer assembly dispensing the combination of the first flowable material and the second flowable material, the nozzle disposed in line with the first axial direction of the first flowable material through the first conduit.

5 In still further example embodiments, a thickness of the gap in the printer assembly is less than half the thickness of the flow channel in the distributor.

 In yet further example embodiments, the flow channel of the flow distributor in the printer assembly spirals around the gap, the spiral flow channel feeding the second flowable material received from the second conduit into the gap. A distance
10 between the spiral flow channel and a core of the flow distributor conveying the first flowable material varies along a length of the spiral flow channel. In one embodiment, the flow distributor is located between two assembled hot end body components of the printer assembly.

 In still further example embodiments, the first flowable material is a different
15 material than the second flowable material.

 In further example embodiments, the printer assembly includes multiple flow distributors such as a first flow distributor, the gap is located at a first junction of the first flowable material and second flowable material. The printer assembly further comprises: a third conduit operative to input third flowable material into a second
20 flow distributor. The second flow distributor includes a second flow channel to deliver the third flowable material into a second thin gap surrounding the junction, the second thin gap being operative to surround the combination of the first flowable material and the second flowable material with the third flowable material flowing to the outlet. In such an instance, the outlet of the flow distributor output signal
25 operative to dispense a combination of the first flowable material, the second flowable material, and the third flowable material.

 In still further example embodiments, the flow distributor of the printer assembly includes an obstruction disposed in a path of the flow channel, around which the second flowable material flows to the gap.

30 In yet further example embodiments, the printer assembly includes multiple heaters., For example, the printer assembly can be configured to include a first heater operative to heat the first flowable material conveyed through the first conduit to a

first temperature and a second heater operative to heat the second flowable material conveyed in the gapped flow channel to a second temperature.

Further embodiments herein include a 3-D printing method comprising:

5 controlling delivery of a first flowable material through a respective port of a first conduit into a flow combiner of a printer assembly, the flow combiner operative to combine multiple types of printable material; controlling delivery of a second flowable material through a second conduit into a flow distributor of the printer assembly, a gapped flow channel of the flow distributor feeding the second flowable material into the flow combiner; and via an outlet of the printer assembly, dispensing

10 a combination of the first flowable material and the second flowable material received from the flow combiner.

In further example embodiments, the controller controls: i) a temperature and pressure of the first flowable material in the printer assembly, and ii) a temperature

15 and pressure of the second flowable material in the printer assembly.

The controller further controls dispensing a combination of the first flowable material substantially surrounded by the second flowable material from the printer assembly.

Further embodiments herein include, via a controller, over time, controlling a

20 volumetric ratio of: i) the input flow rate of the first flowable material into the first conduit, and ii) the input flow rate of the second flowable material into the second conduit. As previously discussed, in one embodiment, the first flowable material differs in material composition from the second flowable material. Alternatively, the first flowable material is the same as the second flowable material.

25 In further example embodiments, the flow distributor of the printer assembly is a first flow distributor, wherein the gapped flow channel is a first gapped flow channel, the method further comprises: via a third conduit, inputting a third flowable material into a second flow distributor of the printer assembly. In one embodiment, the second flow distributor includes at least one flow channel disposed around a

30 second thinner gapped flow channel operative to surround the combination of the first flowable material and the second flowable material with the third flowable material.

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The method further includes: via the outlet dispensing a combination of the first flowable material, the second flowable material, and the third flowable material.

The controller of the printer assembly controls the volumetric ratio of the first flowable material to the second flowable material in an extrusion from the outlet of
5 the flow combiner to vary from 0 to 100 percent.

In further example embodiments, a manufactured component fabricated via the methods as discussed herein includes: one or more extrudates, wherein the extrudates comprise an inner material and outer material, and a composition of the inner material and outer material constituting the extrudates varying as a function of
10 the extrudate position.

Further embodiments herein include a printed component comprising: a combination of at least the first flowable material and the second flowable material, the combination of the first flowable material and the second flowable material dispensed from the outlet of the printer assembly. The material dispensed from the
15 printer assembly forms one or more extrudates deposited on a substrate. The extrudates comprise an inner material and outer material, in which a composition of the inner material and outer material constituting the extrudates varying as a function of the extrudate position.

In still further example embodiments, the first flowable material differs in
20 material composition to the second flowable material.

Further embodiments herein include an apparatus such as a 3-D printed component comprising: a substrate; and a first printed road disposed on the substrate, the first printed road comprising first flowable material and second flowable material
25 dispensed as a first extrusion from a 3D printer assembly onto the substrate, the second flowable material enveloping the first flowable material in the first extrusion.

In one embodiment, the first printed road on the substrate of the apparatus comprises the first flowable material enveloped by the second flowable material.

In still further example embodiments, the component includes a second
30 printed road, the second printed road comprising the first flowable material and the second flowable material dispensed as a second extrusion from the 3D printer

assembly. The second flowable material envelopes the first flowable material in the second extrusion.

In further example embodiments, the second extrusion of the 3-D printed component is disposed on the first extrusion in which the first extrusion resides
5 between the substrate and the second extrusion. The second extrusion is disposed on the substrate, the second extrusion being parallel with the first extrusion. Alternatively, the second extrusion is not parallel with the first extrusion.

In further example embodiments, a volumetric ratio of the first flowable material to the second flowable material in the first extrusion varies over a length of
10 the first extrusion.

In one embodiment, a diameter of the first flowable material disposed in the second flowable material varies over a length of the first extrusion.

As discussed herein, techniques herein are well suited for use in the field of
15 printer applications and, more specifically, 3D printing in which stacked layers of material outputted from multiple passes of a printer nozzle produce a component. However, it should be noted that embodiments herein are not limited to use in such applications and that the techniques discussed herein are well suited for other applications as well.

Note that any of the resources as discussed herein can include one or more
20 computerized devices, fabrication equipment, sensors, servers, communication systems, controllers, workstations, user equipment, handheld or laptop computers, or the like to carry out and/or support any or all of the method operations disclosed herein. In other words, one or more computerized devices or processors can be
25 programmed and/or configured to operate as explained herein to carry out the different embodiments as described herein.

Yet other embodiments herein include software programs to perform the steps and operations summarized above and disclosed in detail below. One such embodiment comprises a computer program product including a non-transitory
30 computer-readable storage medium (i.e., any computer readable hardware storage medium) on which software instructions are encoded for subsequent execution. The instructions, when executed in a computerized device (hardware) having a processor,

program and/or cause the processor (hardware) to perform the operations disclosed herein. Such arrangements are typically provided as software, code, instructions, and/or other data (e.g., data structures) arranged or encoded on a non-transitory computer readable storage medium such as an optical medium (e.g., CD-ROM),
5 floppy disk, hard disk, memory stick, memory device, etc., or other medium such as firmware in one or more ROM, RAM, PROM, etc., or as an Application Specific Integrated Circuit (ASIC), etc. The software or firmware or other such configurations can be installed onto a computerized device to cause the computerized device to perform the techniques explained herein.

10 Accordingly, embodiments herein are directed to a method, system, computer program product, etc., that supports operations as discussed herein.

One embodiment includes a computer readable storage medium and/or system having instructions stored thereon. The instructions, when executed by the computer processor hardware, cause the computer processor hardware (such as one or more co-
15 located or disparately processor devices or hardware) to: control delivery of a first flowable material through a respective port of a first conduit into a flow combiner of a printer assembly, the flow combiner operative to combine multiple types of printable material; control delivery of a second flowable material through a second conduit into a flow distributor of the printer assembly, a gapped flow channel of the flow
20 distributor feeding the second flowable material into the flow combiner; and via an outlet of the printer assembly, control dispensing of a combination of the first flowable material and the second flowable material received from the flow combiner.

The ordering of the steps above has been added for clarity sake. Note that any of the processing steps as discussed herein can be performed in any suitable order.

25 Other embodiments of the present disclosure include software programs and/or respective hardware to perform any of the method embodiment steps and operations summarized above and disclosed in detail below.

It is to be understood that the system, method, apparatus, instructions on computer readable storage media, etc., as discussed herein also can be embodied
30 strictly as a software program, firmware, as a hybrid of software, hardware and/or firmware, or as hardware alone such as within a processor (hardware or software), or within an operating system or a within a software application.

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As discussed herein, techniques herein are well suited for use in the field of providing improved wireless connectivity in a network environment. However, it should be noted that embodiments herein are not limited to use in such applications and that the techniques discussed herein are well suited for other applications as well.

5 Additionally, note that although each of the different features, techniques, configurations, etc., herein may be discussed in different places of this disclosure, it is intended, where suitable, that each of the concepts can optionally be executed independently of each other or in combination with each other. Accordingly, the one or more present inventions as described herein can be embodied and viewed in many
10 different ways.

Also, note that this preliminary discussion of embodiments herein (BRIEF DESCRIPTION OF EMBODIMENTS) purposefully does not specify every embodiment and/or incrementally novel aspect of the present disclosure or claimed invention(s). Instead, this brief description only presents general embodiments and
15 corresponding points of novelty over conventional techniques. For additional details and/or possible perspectives (permutations) of the invention(s), the reader is directed to the Detailed Description section (which is a summary of embodiments) and corresponding figures of the present disclosure as further discussed below.

20 BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1A, 1B, and 1C are example diagrams illustrating isometric and orthographic hidden line drawings of a printer assembly (unity design) according to embodiments herein.

FIGS. 2A, 2B, and 2C are example diagrams illustrating isometric and
25 orthographic hidden line drawings of a printer assembly (duality design) according to embodiments herein.

FIGS. 3A, 3B, and 3C are example diagrams illustrating isometric and orthographic hidden line drawings of a printer assembly (duality mixer design) according to embodiments herein.

30 FIGS. 4A and 4B are example diagrams illustrating isometric and orthographic hidden line drawings of a printer assembly (duality mixer design) according to embodiments herein.

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FIGS. 5A, 5B, and 5C are example diagrams illustrating exploded isometric pictorial view of a printer assembly (such as Triplex design) according to embodiments herein.

FIGS. 6A and 6B are example diagrams illustrating section and detail of a printer assembly (such as Triplex design) according to embodiments herein.

FIG. 7 is an example diagram illustrating cross-sections of different co-extrudates according to embodiments herein.

FIGS. 8A, 8B, and 8C are example diagrams illustrating isometric and orthographic views of a printer assembly (such as Quintet) according to embodiments herein.

FIG. 9 is an example diagram illustrating section and detail views of a printer assembly (such as Compact) according to embodiments herein.

FIG. 10 is an example diagram illustrating an internal view of a printer assembly and corresponding flow of material according to embodiments herein.

FIG. 11A is an example diagram illustrating an internal view of a printer assembly and corresponding flow of material according to embodiments herein.

FIG. 11B is an example diagram illustrating a top view of a printer assembly and corresponding flow of material according to embodiments herein.

FIG. 11C is an example diagram illustrating a side view of a printer assembly and corresponding flow of material according to embodiments herein.

FIG. 12 is an example diagram illustrating a workflow associated with a FD3M method according to embodiments herein.

FIG. 13 is an example diagram illustrating of an FD3M method according to embodiments herein.

FIG. 14 is an example diagram illustrating implementation of a printer assembly to produce a 3-D printed compote according to embodiments herein.

FIG. 15A is example diagram illustrating multiple layers of excursions from a printer assembly according to embodiments herein.

FIG. 15B is example diagram illustrating an extrusion according to embodiments herein.

FIG. 16 is an example diagram illustrating example computer hardware and software operable to execute operations according to embodiments herein.

FIG. 17 is an example diagram illustrating a method according to embodiments herein.

The foregoing and other objects, features, and advantages of the invention will be apparent from the following more particular description of preferred embodiments herein, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, with emphasis instead being placed upon illustrating the embodiments, principles, concepts, etc.

10 FURTHER DESCRIPTION OF EMBODIMENTS

In one embodiment, a printer hot end body comprises: i) a first conduit operable to convey first flowable material received from a first delivery system; and ii) a second conduit operable to convey second flowable material from a second delivery system. The printer hot end assembly further comprises a hot end body and a nozzle. The hot end body is in communication with the first conduit and the second conduit. The flow channels within the hot end body are designed to orient the flow of the first flowable material relative to the second flowable material. The nozzle dispenses processed matter (such as the first flowable material, second flowable material, and/or combinations thereof) received from the upstream conduits.

More specifically, FIGS. 1A, 1B, and 1C depict an FD3M hot end 1 (a.k.a., printer assembly supporting 3D printing of components) referred to as “Unity” so named given its single body component design and single temperature control. In the “Unity” design, the temperatures of the materials being processed will be quite similar, typically within 10 degrees Celsius of a setpoint (such as any suitable temperature setting) controlled with feedback from a temperature sensor. In hot end body 1, two flowable materials are admitted from corresponding upstream delivery systems.

For example, via control provided by controller 140, a first flowable material 91 enters through a first conduit 11 in hot end body portion 1b that is angled relative to the axis of a nozzle (not shown) that threads onto threaded engagement means 21. The first conduit 11 is connected to bend 12 and thereby drop 13.

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Via control provided by the controller 140, a second flowable material 92 enters through second conduit 14 in hot end body portion 1a. In one embodiment, the controller 140 controls a first rate and/or pressure of inputting flowable material 91 into conduit 14 and a second rate and/or pressure of inputting flowable material 92 into conduit 11.

In further example embodiments, the printer assembly 1 includes a first heater 50-1 disposed at any suitable one or more locations of the printer assembly 1; the controller 140 controls an amount of heat applied to the first flowable material 91 conveyed through the first conduit 11 such that the flowable material 91 is set to one or more different temperatures at different lengths of the conduit 11. The printer assembly 1 includes a second heater 50-2 disposed at any suitable one or more locations of the printer assembly 1; the controller 140 controls an amount of heat applied to the second flowable material 92 conveyed through the second conduit 11 and flow distributor 8 such that the flowable material 91 is set to one or more different temperatures as the second flowable material 92 passes through the flow distributor 8 into the junction 19.

In further example embodiments, note that the flow channel 17 of the flow distributor 8 includes a flow channel 17 that spirals around the thinner gap (such as provided by conical flow channel 18). In such an instance, the spiral flow channel 17S feeds the second flowable material 92 received from the second conduit 14 into the thinner gap channel.

In still further example embodiments, a distance between the spiral flow channel and the thinner gap (provided by the conical flow channel 18 with port 11P) with respect to the y-axis varies along a length of the spiral flow channel.

Note further that the printer assembly 1 also includes any number of additional heaters operative to control a temperature of the flowable material passing through junction 19 and conduit between junction 19 and the nozzle 20N.

In one embodiment, the flow distributor 8 is located between two assembled hot end body components of the printer assembly 1.

The terminal end of the conduit 11 includes a respective port 11P that inputs the respective flowable material 91 into the junction 19. As further discussed below,

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the junction 19 of the printer assembly 1 provide a chamber in which the flowable material 91 is combined with (such as enveloped by) the second flowable material 92.

In one embodiment, to achieve predominantly axisymmetric flow of the flowable material 92 into the junction 19 (such as flow combiner) in order to surround
5 or envelope the first flowable material 91, the second conduit 14 is split or bifurcated into two diagonal drops 15a and 15b that subsequently connect to vertical drops 16a and 16b. These vertical drops direct the second flowable material 92 to opposing sides of annular flow channel 17 (V-shaped from side view and conical in 3D) that then connects to converging conical flow channels 18.

10 In one embodiment, the flow channel 17 and the conical flow channel 18 (a.k.a., gap, channel gap, further comprising, etc.) represent a so-called flow distributor 8 of the printer assembly 1. In one embodiment, the flow resistance in the annulus (flow channel 17) is substantially less than the flow resistance in the converging conical flow channels (18), a predominately axisymmetric flow is
15 achieved at the junction 19 (flow combiner) where the first and second flowable materials combine. In other words, the conical flow channel 18 (gap) is thinner than the annular flow channel 17.

As further shown, the conical flow channel 18 and/or corresponding end of conduit 11 includes port 11P from which the first flowable material 91 enters the
20 junction 19 (flow combiner). As previously discussed, the flow of the second flowable material 92 from the conical flow channel 18 surrounds or envelops the first flowable material 91 entering into the junction 19 through the corresponding port 11P.

In one embodiment, the gap provided by the conical flow channel 18 is a circumferential gap substantially surrounding the junction 19 to envelope the first
25 flowable material 91 (received from port 11P) with the second flowable material 92 as the first flowable material 91 and the second flowable material 92 pass through the junction 19.

In further example embodiments, note that the flow channel 17, conical flow channel 18, and the junction 19 can be implemented in a manner such that the second
30 flowable material 92 is inputted with equalized pressure (such as the pressures being within 10% in magnitude or other suitable value with respect to each other) radially into or towards the junction 19. In such an instance, the second flowable material 92

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forms a layer or coating on the first flowable material 91 of substantially uniform thickness. However, note that the thickness of the coating and offset with respect to the center axis of the extrusion from the printer assembly 1 may vary as well via variations in pressure of supplying the second flowable material into the junction 19.

5 As previously discussed, the first conduit 11 and corresponding port 11P provides flow of the first flowable material 91 in a first axial direction (such as along the Y-axis); the flow distributor 8 is operative to direct a flow of the second flowable material 92 in multiple directions from conical flow channel 18 (gap) into junction 19, which are different from the first axial direction (Y-axis).

10 In one embodiment, this axisymmetric flow of the combined materials is substantially maintained downstream through the outlet 20 (such as a hot end orifice) of the printer assembly 1 and subsequent nozzle 20N connected to threaded engagement means 21. In further example embodiments, the outlet 9 of the junction 19 extends to a nozzle (such as outlet 20) of the printer assembly 1, resulting in
15 dispensing of the combination of the first flowable material 91 and the second flowable material 92. In one embodiment, the nozzle 20N is disposed in line with the first axial direction (Y-axis) of the first flowable material 91 received through the first conduit 11 and corresponding port 11P.

For reference, in one embodiment, the size of the conduits is 1 to 3 mm with
20 the preferred cross-section being circular with a diameter of 2 mm, although these dimensions can vary depending on the embodiment. In one nonlimiting example embodiment, the annular flow channel 17 has a major diameter of 8 mm with a circular cross section having a diameter of 2 mm. The converging conical flow channel 17 (thinner gap) has a length of 3 mm and a preferred minimum thickness of
25 1 mm or less. The diameter of the drop 13 is 1 mm while the diameter of the flow channel between junction 19 (flow combiner) and outlet 20 (hot end orifice) is 2 mm. Of course, these stated preferences are for typical polymeric flowable materials (e.g. ABS, PLA, HIPS, PC, etc.) at typical processing conditions, and other values may be derived based on well-known trade-offs between melt residence time, shear rate, and
30 pressure drop such as stated in Kazmer's Injection Mold Design Engineering textbook that are directed to melt flow.

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In one embodiment, a thickness of the thinner gap provided by the conical flow channel 18 is less than half the thickness of the flow channel 17 of the flow distributor 8, although the thickness of the thinner gap provided by the conical flow channel 18 can be any suitable dimension such as less than the thickness of the flow channel 17..

In yet further example embodiments, the controller 140 controls, over time: i) the flow rate of the first flowable material 91 inputted into to the first conduit 11, and ii) the flow rate of the second flowable material 92 into the second conduit 14. The resulting extrusion outputted from the outlet 9 of the printer assembly 1 varies between 0 and 100 percent of the first flowable material 91 and between 100 and 0 percent of the second flowable material 92.

FIGS. 2A, 2B, and 2C depicts an FD3M hot end body referred to as the “Duality Coex.” This name stems from the use of two heaters and improved thermal isolation compared between connected body portions 2a and 2b relative to the body portions 1a and 1b composing the “Unity” design.

In this example embodiment, the implementation of printer assembly 1 includes a spiral flow distributor 8S within the hot end that is comprised of spiral flow channels 22S (akin to flow channel 17 as previously discussed, but spiraled) defined by the volume between surface 23 in hot end portion 2a and surface 24 on hot end portion 2b. Namely, both the mandrel and cavity portions of the hot end contribute to the spiral flow behavior of the flowable materials during processing. As will be later seen, the spiral flow mandrel may also be comprised of a primarily conical (non-helical or spiral section) in the mandrel or the die cavity with the spiral flow channels residing within the opposing member.

In operation, the second flowable material 92 flows through second conduit 22 and into the spiral flow channel 22s defined by the volume between surfaces 23 and 24. As the melt of material 91 and 92 continues, the diameter of the helical channels diminishes relative to the thickness of the conical gap between the mandrel and die cavity. In such an instance, the spiral flow channel 22s is created as a helical loft with a pitch of 3 mm and a converging taper angle of 30 degrees. The helical loft starts as a circular section having a diameter of 2 mm at the inlet and ends as a circular section

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having a diameter of 0.8 mm after three rotations. This ending diameter matches the thickness of the conical section at outlet 25. As a result, the flow of the second flowable material 92 progresses from a primarily radial direction at the inlet of spiral flow channel 22s to a primarily axisymmetric flow at the conical outlet 25 where the second flowable material will join with the first flowable material entering the junction 19 such as hot end body portion 2a.

As a result, via control (provided by controller 140) of flowable material 91 into conduit 2 and control of flowable material 92 into conduit 22, the printer assembly 1 produces a stable and concentric coextrusion delivered to and outputted from the hot end outlet 26 in which the second of flowable material 92 envelops the first flowable material 91.

This so-called “Duality Coex” embodiment also provides features directed to thermal isolation for improved temperature control. Specifically, the two heaters 27a and 27b are used to deliver heat to body portions 2a and 2b in response to temperature feedback from temperature sensors inserted into monitoring ports 28a and 28b. To provide temperature isolation, a gapped flow channel 29 (such as a gap) extends inwardly between body portions 2a and 2b, such that the heat transfer is reduced between body portions 2a and 2b of FIG. 2A. The use of this gap will tend to make body portion 2a slender and weaker. Accordingly, rails 30 are provided on both sides of the hot end to provide stability to body portion 2a. To reduce direct heat transfer between the heaters, slots 31a and 31b are provided to minimize direct heat transfer to the rails. Furthermore, since the rails are long and slender, the heat transfer is minimized between the two body portions 2a and 2b. In the “Duality” design, the temperatures of the materials being processed can differ somewhat, typically more than 10 degrees Celsius of a setpoint controlled with feedback from two or temperature sensors.

FIGS. 3A, 3B, and 3C depict an FD3M hot end referred to as the “Duality Mixer.” This name denotes it’s a derivative of the “Duality Coex” design but with mixing capabilities.

In the “Duality Mixer”, a first flowable material 91 is conveyed through a first conduit in hot end body portion 3b. To assist mixing, the conduit is split into four

flow channels 32a-d with channels 32a and 32c falling in the cutting plane of the section and flow channels 32b and 32d falling normal to the cutting plane and, as such, are not shown because they are out of view.

5 Differing from the “Duality Mixer” where the two material join near the outlet of the spiral flow distributor, the first flowable material in the “Duality Mixer” enters near the top of the helical flow channel where it encounters the second flowable material being conveyed from the second conduit in hot end body portion 3a. In this particular design, 28 mixing elements such as mixing pins 33a, 33c, and 33z span the gap between the inner and outer surfaces defining the volume of the spiral flow distributor. Thus, in one embodiment, the flow distributor 8D includes one or more
10 obstructions (such as mixing pins 33a, 33c, and 33z) disposed in a path of the flow channel to the junction 19.

In one embodiment, each of the mixing pins is cylindrical in shape with a diameter that equals 1 mm (or other suitable value) and a length that spans the
15 distance from the inner and outer surfaces of the spiral flow distributor. As indicated by the oblique cut of some of the mixing element cross-sections such as 33z, each mixing pin may have varying orientation to improve the randomness of the flow field. Since the flowable materials must undergo diverging and converging flows in the thicker and thinner sections of the spiral flow distributor, a high degree of mixing
20 occurs in a relatively short flow length with relatively low pressure drop.

Note that this design may be analyzed and optimized with finite element simulation tools such as computational fluid dynamics (e.g. ANSYS/Fluent), preferably with non-Newtonian material constitutive models with non-isothermal heat transfer including viscous heating.

25 The hot end body may be made by bronze, brass, or aluminum casting using 3D printed patterns to define the geometry of the hot end. Alternatively, the hot end body may be made by binderjet printing and sintering of stainless steel. Direct metal laser sintering of aluminum has also been found feasible.

In some cases, finish machining of useful features such as flow channel bores and threads is performed. We have found, however, that most surfaces are sufficiently
30 functional such that finish machining is not required. In some cases, however, the flow channel bores may be clogged by steel powder residue that was not removed

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prior to sintering. Such clogs have been found common when the diameter of the flow channels are less than 2 mm and when the length:diameter aspect ratio is greater than 10:1. In such cases, finish machining may be used to clear the flow bore when the hot end body and flow channel geometry allows.

5 Subsequent embodiments include comprised of two or more hot end body components are purposefully designed to support inspection and finish machining. We have also found that it can be beneficial to employ sanding cord with grits of 150-1500 and diameters of 1-2 mm to polish the inside surfaces of flow channels.

10 FIGS. 4A and 4B illustrate an embodiment referred to as the “Duality V3”. In this embodiment, two different materials A (91) and B (92) are fed into a hot end 4 as indicated by arrows labeled “A” and “B”. The materials are delivered via corresponding extruders 36a and 36b. Each extruder has a conduit 37a and 37b for delivering material that also serves as a heat break for reducing transfer from the hot
15 end to the extruders. While extruders such as the Hemera supplied by E3D (such as Isle of Wight, United Kingdom) for processing feedstock in the form of filament may be used as depicted in FIG. 4B, other material delivery systems may be directly with the hot end including, for example, a paste dispenser, syringe pump, gear pump, plasticating screw, proportional valves, injection unit, and others. The materials
20 supplied to the conduit inlets of the hot end in this and other embodiments may be delivered at any suitable specific temperatures, pressures, and flow rates with sensors and actuators as appropriate to their processing.

 A coupling nut 39a secures extruder 36a to hot end body 40 while a coupling nut 39b secures extruder 36b to hot end body 41. The coupling nuts are hexagonal in
25 shape with an outer width exceeding the diameter of the threaded engagement portion of the heat breaks 37a and 37b. In this specific embodiment, the heat breaks have an M6 thread while the width of the coupling nuts are 10 mm. One or more arrows 39b4 is provided on the exterior of the coupling nut to assist with orientation and use in system assembly. Each coupling nut is provided with a right hand threaded portion
30 39a1 at the start of the coupling nut wherein the “start” is defined as the end nearest the start of the provided arrow. Each coupling nut is also provided with a left hand threaded portion 39a2 at the end of the coupling nut wherein the “end” is defined as

the end nearest the end of the provided arrow. A deeper bore 39a3 is provided at the center portion of the coupling nut. In use, the right hand and left hand threads of the coupling nut cause the threaded portions on the two members 37a and 40 to be pulled together or pushed away as a function of the coupling nut. The deeper bore 39a3 provides for slop in the axial location of the coupling nut relative to the mating surfaces of the members 37a and 40. A site hole such as 39b5 may be provided to verify the location of the mating surface. While the coupling nut has been shown feasible, latter designs eliminated the use the coupling nut by using a threaded female cavity in the hot end body into which heat breaks 37a and 37b directly threaded.

In the “Duality v3” design, the hot end 4 is comprised of separate body components 40 and 41. This design was found to be advantageous for two reasons. First, the use of two separate body components allows the parts to be produced separately such that each part is easier to be produced with lower chance of clogs. Second, the use of two separate body components allows for the inspection of each component as well as simpler finish machining. As shown in FIG 4, this embodiment shares many similar features with other embodiments such as a spiral flow distributor 8S (including spiral channels 17S and gap), gap for thermal isolation, and separate heaters H1 and H2 that provide heating power in response to feedback from temperature sensors T1 and T2. While the helical loft is provided in the die cavity portion of hot end body component 41, portions or the entirety of the spiral flow channel may also be provided in the mandrel portion of hot end body component 40.

The FD3M “Duality v3” print head assembly 4p is comprised of the hot end 4, mounting bracket 42, material delivery systems, and related components such as the heat breaks, coupling nuts, heaters, temperature sensors, nozzle, etc. The mounting bracket 42 serves at least two purposes. First, it locates and supports the material delivery systems 36a and 36b so that the hot end body components 40 and 41 are properly aligned with respect to each other and the material delivery conduits 37a and 37b. Second, the mounting bracket 42 also locates and supports the entirety of the print head assembly relative to the printer’s frame or printer’s moving stage(s). As indicated in FIG 4, the mounting bracket may be supplied with fasteners such as 43 or rollers. In this specific design, the mounting bracket 42 is designed to mate with the carriage of a Creality CR10 3D printer and item 44 is a front plate that supports a

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roller (not shown as it is located behind the plate 44) that engages a lateral rail upon which the print head assembly 4p traverses. Of course, other printing configurations for controlling the location of the print head assembly relative to a build plate can be readily devised, and the inventive features described herein applied thereto.

5 The “Duality v3” design also discloses a nozzle that may be used with many of the embodiments. In this design, a nozzle 41N has a protrusion with external threads that engage with internal threads located at the outlet of hot end body portion 41. It is common for nozzles to have a metric thread with a nominal diameter of 6 mm and a pitch of 1 mm, referred to an M6 thread. While nozzles having an M6 thread
10 can be used with the FD3M embodiments described herein, we have found that smaller nozzles are sometimes preferred in order to minimize the internal volume of the extrudate so as to minimize the changeover time during changes in material composition. Accordingly, the nozzle 41N may be designed according to an M4 thread, with a nominal outer diameter of 4 mm and a pitch of 0.7 mm. The height of
15 the nozzle is just 5 mm with an inlet diameter of 0.8 mm that transitions to a 0.4 mm diameter with a land length of 1.6 mm at the outlet. Accordingly, the volume of the melt within the nozzle is less than 2 cubic millimeters. Even smaller nozzles based on an M3 design have been made with smaller volumes, but the M4 design is preferred since it is slightly easier to handle and supports nozzle orifice diameters up to 1 mm.
20 Nozzle outlet orifice diameters are typically on the order of 0.1 to 2 mm, with a typical diameter being 0.4 mm. Printed road widths are typically 0.8 to 1.5 times the nozzle orifice diameter with road heights equal to 10 to 100 percent of the nozzle orifice diameter.

25 FIGS 5A-5C and 6A and 6B disclose a “Triplex” design for processing of three materials A, B, and C. As shown in FIG 5A-C, a material “A” (91) is conveyed by an extruder in a first direction 45 to and through a first hot end body component 46. A material “B” (92) is conveyed by an extruder in a second direction 47 to and through a second hot end body component 48. A material “C” (93) is conveyed by an
30 extruder in a third direction 49 to and through a second hot end body component 49.

In this particular embodiment, the hot end body components are configured with spiral flow distributors for concentric coextrusion of the materials. However, one

of more of the body components can also be configured with mixing elements to dispense a blend of two or more admitted materials. The location and directions 45, 47, and 49 of the admitted materials are configured such that the extruders may be located and connected for the conveyance of the respective materials. In FIG 5A, the inlets to the hot end body components 46, 48, and 50 are designed to be generally orthogonal to each other with direction 45 defining the centerline of the hot end body components. However, there is no requirement for such positioning and the directions may be at 30, 45, or 60 degrees or some other angle as desired.

FIGS. 6A and 6B provide a section and detail views of the “Triplex” print head assembly 5p with an example of the processed coextruded filament 55 (a.k.a., extrusion, road, layer of material, etc.). Comporting with the component design of FIG 5A-C, FIG 6A-B shows the assembled design of the hot end body components 46, 48, and 50 for processing materials “A” (91), “B” (92), and “C” (93). At a first portion of junction 19 (flow combiner), material “A” is extruded into the core of material “B”, then the coextruded material “A in B” is coextruded into material “C” at a second portion of junction 19 (flow combiner) to provide a co-extrudate 55 consisting of “A in B in C”. This co-extrudate is fed into a nozzle 51 that can further reduce the diameter of the co-extrudate. For example, nozzle 51 in FIG 6A-B has a preferred inlet diameter of 0.8 mm and a preferred outlet diameter of 0.4 mm, though the preferences for these dimensions may be readily scaled in application by a factor of 4 or more.

In operation, the volumetric flow rates of materials “A”, “B”, and “C” from their respective extruders 52, 53, and 54 determine the composition and deposited volume of co-extrudate 55. TABLE 1 provides some example material feed rates and resulting co-extrudate diameters for feedstock filament diameters of 1.75 mm and outlet nozzle diameter of 0.4 mm corresponding to the cross-sections depicted in FIG 7. In TABLE 1, the columns V_A, V_B, and V_C correspond to the driven filament velocities of materials “A”, “B”, and “C” by the extruders in units of mm/s. The resulting total flow rate is Q_Tot in units of cubic millimeters per second. The resulting diameters of the materials “A”, “B”, and “C” within the co-extrudates 55 to 61 are respectively indicated by the columns D_A, D_B, and D_C. The require print

speed of the 3D printing process to conserve the volumetric flow rates are provided in column V_Print with units of mm/s.

TABLE 1: EXAMPLE MATERIAL FEEDS AND COEXTRUDATES

5	ITEM	V_A	V_B	V_C	Q_Tot	D_A	D_B	D_C	V_Print
	55	1	1	1	7.2	0.23	0.33	0.4	57.4
	56	2	0	0	4.81	0.4	N/A	N/A	38.25
	57	0	2.5	0	6.51	N/A	0.4	N/A	47.85
	58	0	0	4	9.6	N/A	N/A	0.4	76.5
10	59	1.25	1.25	0	6.015	0.28	0.4	N/A	47.85
	60	1.5	0	1.5	7.21	0.28	N/A	0.4	57.4
	61	0	1	0.5	3.61	N/A	0.33	0.4	28.7

Regarding the data indicated in TABLE 1, it is understood that conservation of volume largely governs the flow of the extruded materials such that the materials are dispensed at the hot end outlet in proportion to the material feed rates provided at the inlet. Compressibility and die swell effects may occur such that the outer coextrudate diameter is somewhat larger than the nozzle orifice diameter depending on the material properties and processing conditions; the feed rates may be adjusted based on conservation of volume and compressible flow models as well as empirical and other analytical models to achieve desired dispensing. Furthermore, it is understood that the actual print speed might be faster or slower than these coextrudate speeds, such that the dimensions of the resulting coextrudate may purposefully differ from those indicated in TABLE 1. For example, if the nominal print speed for printing item 55 were four times the coextrudate speed, then the cross sectional area of the coextrudate would necessarily be one fourth of nozzle orifice. This factor of four reduction is referred to as draw ratio, and it is understood that a draw ratio of four would result in a halving of the diameter of the coextrudate and the diameters of the material contained therein such that D_A, D_B, and D_C in item 55 would respectively be 0.115, 0.165, and 0.2 mm. Draw ratios can also be less than 1, resulting in larger coextrudate diameters than the nozzle orifice.

As indicated by the examples of TABLE 1 and FIG 6 and the associated written description, the extruder speeds and print speed and nozzle orifice may be selected to obtain a wide variety of coextrudate designs, and to vary the coextrudate composition during the printing of a product. Given that the nozzle 51 is quite small, the composition of the coextrudate may be varied on the fly, for example, to switch from a coextrudate “A in B in C” to a single extrudate of “A” or “B” or “C” and then to a coextrudate of “A in B” or “A in C” or “B in C” and then back again to other combinations as desired. The amount of material required to perform a switch is quite small, on the order of millimeters. If this transition length is unacceptable in some applications, the transition coextrudate may dispensed into a purge bucket or printed in a purge tower to ensure a stable coextrudate in the printed product.

FIGS. 8A-8C depict isometric and front views of a “Quintet” hot end design 7 according to one of the inventive embodiments. The hot end 7 is composed of a hot end body component 7a attached to a hot end body component 7b. Hot end body component 7a provides a distributor with mixing elements protruding into spiral flow channel residing with hot end body component 7b; there is no requirement for the mixing elements or spiral flow channels to reside solely in one of the body components and they may located in the other component or both components differing in a manner than shown in FIGS. 8A-8C. Hot end body components 7a and 7b are provided with one or more conduits connected to extruders in a manner similar to those previously described. In the example of FIGS. 8A-8C, hot end body component is provided with one inlet for receiving a material “A” while hot end body component 7b is provided with for inlets for receiving materials “B”, “C”, “D”, and “E”.

In operation, as described for the “Triplex” design, the extruders may provide varying flows of the inlet materials. Unlike the “Triplex” design, however, the “Quintet” design is provided with a mixing section to dispense a blend of the five materials. The materials may vary the mechanical, electrical, chemical, color, or other physical properties as desired by varying the properties of the feedstock materials and the relative rates of flow. For example, TABLE 2 provides recipes for dispensing materials of various colors “F” in the direction of the arrow 67 where material “A” is

the color white, material “B” is the color yellow, material “C” is the color red, material “D” is the color blue, and material “E” is the color black; other colors are readily provided by adding other materials and the shade and intensity of the colors may be fine-tuned by characterizing the color properties of the feedstock materials.

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TABLE 2: MATERIAL PROPORTIONS AND RESULTING COLORS

2 RED + 1 BLUE → MAGENTA

1 RED + 1 BLUE → VIOLET

1 RED + 2 BLUE → PURPLE

10 1 YELLOW + 2 BLUE → TEAL

1 YELLOW + 1 BLUE → GREEN

2 YELLOW + 1 BLUE → CHARTREUSE

2 YELLOW + 1 RED → AMBER

1 YELLOW + 1 RED → ORANGE

15 1 YELLOW + 2 RED → VERMILLION

1 WHITE + 1 BLACK → GREY

2 RED + 1 BLACK → MAROON

1 WHITE + 1 RED → PINK

2 YELLOW + 1 BLACK → BROWN

20 2 BLUE + 1 BLACK → NAVY

1 WHITE + 1 BLUE → LIGHT BLUE

For best operation, the material inlet locations in FIGS. 8A-8C are ordered according to the darkness of the material with darker material being injected later in the flow stream to reduce the amount of melt volume required to flush the system. In operation, it is also desirable to slightly retract the unused filament colors when blending other materials in order to avoid contamination of the blend. For instance, it is desirable to slightly retract the yellow, blue, and black filaments when starting to mix white and red in order to minimize contamination of the blended pink color.

30 While this example pertains to color, similar concepts apply to other materials and the blending of their properties. Furthermore, while the embodiments of the print head assemblies with extruders (e.g., FIGS. 4, 5, 6, and 8) show the extruders directly

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connected to the hot ends' conduit inlet, it is understood that a Bowden-style drive may also be used for one or more connected extruders. The use of a Bowden extruders is beneficial in the "Quintet" design by of FIG. 8A-8C reducing the size and mass of the print head system that would otherwise have to be supported on a moving stage.

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FIG. 9 provides a "Compact" design according to embodiments herein. In this design, the hot end body comprises a main body 81 with a nozzle 82 secured with a retaining plate 83. Four M3 socket head cap screws mate with the upper surface 81s of the main body 81 and pass through holes 81h to threadably engage tapped holes (not shown) in the retaining plate 83. To assist in accurately locating the nozzle 82 and retaining plate 83 relative to the main body 81, one or more locating pins 84 or other mating features may be disposed in the main body, nozzle, and/or retaining plate.

As with other embodiments, the main body 81 received flowable materials through upstream conduits into flow channels 81a and 81b. The flowable materials are then respectively provided to vertical flow bores 81c and 81d before entering a flow distributor. The flow distributor in the "Compact" design may be located between the mating surfaces of the main body 81 and the nozzle 82. Two variants of the flow distributor are depicted in FIG 9. Distributor 82b relies on two bifurcations of the outer flowable material such that four generally orthogonal flows enter a thin gap at the junction of the outer material around the inner material. Another distributor design 82s relies on a converging spiral flow channel wherein the diameter and pitch of the spiral decrease as a function of the angular position of the spiral so that a generally axisymmetric flow of the outer material is achieved in the thin gap at the junction of the outer material around the inner material.

The design of FIG 9 is desirable due to its simplicity, but other variations are readily conceived and implemented. For example, the flow channels 81a and 81b are each provided at 45 degrees relative to the mating plane of the main body 81 and the nozzle 82 such that the flow channels 81a and 81b are orthogonal to each other. Short vertical bores 81c and 81d are then provided to direct the flow into the flow distributor such as 82b and 82s. However, different angles for the flow channels 81a and 81b are readily provided so that the short vertical bores 81c and 81d are not

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required. For example, a preferred embodiment provides flow channels 81a and 81b at 60 degrees relative to the mating plane of the main body 81 and the nozzle 82 such that the channels 81a and 81b are at 60 degrees relative to each other. By eliminating the vertical bores 81c and 81d, the flow channels 81a and 81b are more easily

5 produced and finished with machining if required.

While the design of FIG 9 is directed to the coextrusion of two materials processed at a single material, the design is readily extended to the processing of three or more materials each processed at a different temperatures by importing features such as air gaps and multiple sensors and heaters such as disclosed for the “Triplex”
10 design of FIG 5. Spiral and other mixing element designs may also be incorporated to blend rather than coextrude the process materials as also disclosed for other embodiments.

The layout, size, and diameter of the flow channels and gaps comprising the distributors may be readily varied to achieve highly axisymmetric flows of the two
15 materials subject to processing temperature and pressure limitations. Generally, more compact designs are preferred. The design of FIG. 9 and results of FIG. 10 correspond to an outer nozzle diameter of 10 mm with inlet bore diameters 81c and 81d being 1 to 1.5 mm. The hydraulic diameter of the flow channel in both distributors 82b and 82s (located below vertical bore 81d) is 1.5 mm. The preferred shape of the cross
20 section is a half ellipse located in the nozzle with a width of 1.5 mm and a depth of 2.1 mm. The vertical gap between main body 81 and nozzle 82 in the vicinity of the junction between the inner and outer materials is typically 0.1 to 1 mm, with a gap thickness of 0.3 mm being preferred. These details are provided as a disclosure of the best mode with the intent to provide a modular design with the geometry of the flow
25 distributor being located entirely in the nozzle 82. As such, varying designs and functionality may be readily implemented and tested just by replacing the nozzle. However, it is possible to provide the flow distributor geometry in the main body 81 or between the main body 81 and the nozzle 82. The latter design would allow the use of “full round” flow channels that are known to provide improved flow and pressure
30 properties while avoiding material hang-up that can cause degradation and impede material changes.

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FIG. 10 is an example diagram illustrating an internal view of a printer assembly and corresponding flow of material according to embodiments herein.

In this example embodiment, via control provided by controller 140, the conduit 91A of printer assembly 1 delivers the flowable material 91 along Y-axis to the inlet of the junction 19.

Additionally, the conduit 91B delivers flowable material 92 to the inlet port 1111 of the flow channel 82B (associated with flow distributor). The flowable material 92 travels from inlet 1111 through the channels 82B to respective diverters 1025-1 and 1025-2 that further split (bifurcate) the flow of flowable material 92 towards the (thin channel) gap 92b. As previously discussed, the flowable material 92 passes through gap 92B to the junction 19 where the flowable material 92 envelops flowable material 91 received from the outlet conduit 91A into the flow distributor.

The combined material (flowable material 92 encasing flowable material 91) passes through the junction 19 (such as in narrowing passage 1052 of junction 19) to outlet 9 of the junction 19 and further to the nozzle 20N (another outlet).

FIG. 11A is an example diagram illustrating an internal view of a printer assembly and corresponding flow of material according to embodiments herein.

In this example embodiment, via control provided by controller 140, the conduit 91A of printer assembly 1 delivers the flowable material 91 along Y-axis to the inlet of junction 19.

Additionally, the conduit 91B delivers flowable material 92 to the inlet port 1111 of the spiral flow channel 82S (or 17S). The flowable material 92 travels from inlet 1111 through the spiral flow channel 82S (or 17S). A cross section of the spiral flow channel tappers along its length. Along a length of the channel 17S, a portion of the flowable material 92 in the flow channel 17S seeps into the gap 18 of the flow distributor to the junction 19.

As previously discussed, the flowable material 92 passes through flow channel 18G such as gap to the junction 19 where the flowable material 92 envelops flowable material 91 received from the conduit 91A. In this example embodiment, the flowable material 92 flows axially inward toward the material 91B passing along the

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Y-axis from the inlet of the conduit 91A to the outlet 9 and corresponding nozzle 20N.

Thus, the combined material (flowable material 92 encasing flowable material 91) passes through the junction 19 (such as in narrowing passage 1052 of junction 19) to outlet 9 of the junction 19 and further to the nozzle 20N where the material is dispensed onto a surface of a 3-D component being fabricated.

Note that full encasement of the flowable material 91 with the flowable material 92 is shown by way of a non-limiting example embodiment only. For example, the spiral flow channel 82S (17S) can be configured to provide 360 degree encasing of the flowable material 91 with flowable material 92.

The spiral flow channel 82S (17S) can be configured to, from view B, provide any value between 0 and 360 degrees of partially encasing the flowable material 91 with the flowable material 92. See FIG. 11B as well.

FIG. 11B is an example diagram illustrating a top view of a printer assembly and corresponding flow of material according to embodiments herein. FIG. 11C is an example diagram illustrating a side view of a printer assembly and corresponding flow of material according to embodiments herein.

In this example embodiment, with reference to FIGS. 11B and 11C as previously discussed, via control provided by controller 140, the conduit 91A of printer assembly 1 delivers the flowable material 91 along Y-axis to the junction 19 disposed in the printer assembly 1.

Additionally, the conduit 91B delivers flowable material 92 to the inlet port 1111 of the spiral flow channel 17S (or 82S). The flowable material 92 travels from inlet 1111 through the spiral flow channel 82S (or 17S). As previously discussed, the cross section of the spiral flow channel tapers along its length. The amount of flowable material 92 passing through the channel 82S reduces between inlet 1111 and location L2 of the channel 82S. For example, the cross section of the spiral flow channel 17S1 at location L1 is larger than the cross section of the spiral flow channel 17S2 at location L2.

In a similar manner as previously discussed, the flowable material 92 passes through flow channel 18G such as a thin gap to the junction 19 where the flowable

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material 92 envelops flowable material 91 received from the conduit 91A. In this example embodiment, the flowable material 92 flows axially inward toward the material 91 passing along the Y-axis from the inlet 1110 of the conduit 91A to the outlet 9 and corresponding nozzle 20N.

5 Thus, the material such as flowable material 92 encases flowable material 91 in the junction 19. The combination of material (such as flowable material 92 encasing the flowable material 91) passes through the junction 19 (such as in a narrowing passage 1052 of junction 19) to outlet 9 of the junction 19 and further to the nozzle 20N where the material is dispensed onto a surface of a 3-D component
10 being fabricated.

FIG. 12 is an example diagram illustrating a workflow associated with a FD3M method according to embodiments herein.

The distributor designs depicted in the prior drawings may be analyzed and
15 optimized with finite element simulation tools such as computational fluid dynamics (e.g. ANSYS/Fluent, or SolidWorks/Flow Simulation), preferably with non-Newtonian material constitutive models with non-isothermal heat transfer including viscous heating. FIG 9 provides one such result wherein the inner material is simulated as high density polyethylene (HDPE) flowing into inlet 91a and the outer
20 material is simulated as polypropylene (PP) flowing into inlet 91b. Each of the materials is specified as flowing at 2 cubic millimeters per second at a temperature of 220 degrees Celsius. The resulting flow paths are respectively depicted as 92b and 92s for the flow distributors 82b and 82s. The flow paths are shown to be generally axisymmetric with pressures estimated to be on the order of 2-4 MPa, which is known
25 to be within typical operating melt pressures of available extruders (typically 10 MPa or greater although they can be any suitable value).

Moving on to the control system design, the described hot end designs have been fitted to a Creality CR10 (Shenzhen, China). The CR10's control board was replaced with an Azteeg X3 Pro (Panucatt Devices, Irvine CA) controller having 8
30 control axes and temperature control zones. The controller firmware relied on Marlin with an Octoprint interface to a supervising PC. To operate the system, the standard workflow for 3D printing is modified to add two additional steps that are represented

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in FIG 10. In a traditional workflow, the STL/CAD geometry 102 is exported from the CAD system such as SolidWorks 101 and provided to a preprocessor/slicer 103 such as Cura or Slic3r. The first additional step is to split the CAD geometry into multiple sub-components 1031, 1032, 1033, 1034, 1035, and 1036 wherein each sub-component may be specified as having a custom extruded material. These sub-components are then assembled in Cura and assigned a tool number corresponding to a virtual extruder. The slicing then proceeds as normal with custom control of the print paths and processing parameters for each extruder. The pre-processor 103 then exports a traditional g-code 104, albeit one with many extruders and tool change commands (T#) that is not quite ready for direct use with the implemented extruders.

To make the g-code 104 ready for use, a program 106 may be used to plan the extruder movements to dynamically dispense the materials. The developed program 106 is referred to as the Matlab Interpreter for Marlin Modeling of Multiple Materials (MI4M) but other programs may be readily deployed including within pre-processors 103 such as Cura. This program 106 reads g-code 104 and outputs a second g-code 107 (referred to as M4 or g+code) that reads Cura's tool changes and maps the tool numbers onto material mappings that determine the extruder actions. The mapping 105 may be represented as a table 105T wherein each virtual extruder is representative of a different fraction of flowable materials. For example, a graduated tensile bar with material proportions varying from 0 to 100% may have 6 tools 1-6 with the materials 1031-1036 proportioned as indicated in Table 105T. These mappings are then used to re-write the g-code to provide material-specific extruder steppings for every line of the g-code. The program also verifies the process planning and removes unsuitable extruder retractions and other control actions that were planned by Cura. The G+Code 107 is then provided to the described Creality CR10 with the Azteeg X3 Pro and implemented hot end to provide a printed part such as the tensile bar 108 with graduated concentrations of the processed flowable materials.

FIG. 13 provides the general methodology for planning and operating the FD3M process. Component geometries with different ratios/blends of the multiple materials are defined at step 111 using conventional solid modeling computer aided design. Print paths are planned at step 113 using virtual extruders corresponding to the

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different ratios/blends of the multiple materials. Typically, the number of virtual extruders will exceed or greatly exceed the number of flowable materials provided by corresponding extruders. The virtual extruders are mapped to physical extruder movements at step 115 according to the specified ratios/blends of the flowable materials such as described with respect to TABLES 1, 2, and 105T. The moves for the virtual extruders are replaced by proportional moves of the physical extruders at step 116 according to the defined mappings. The 3d printing then proceeds at step 118 using the defined extruder movements given the synchronized process movements of the print bed relative to the implement hot end assembly.

The embodiments provided herein are for demonstrative purposes, and not intended to limit or preclude the applications of the described embodiments and there combinations. It is understood that the embodiments may be readily combined with each other. For example, the mixing capability of the “Duality Mixer” or “Quintet” designs may be used to blend materials that are subsequently used by the “Triplex” or “Compact” designs. Many different material systems have been contemplated with some additional materials and applications provided in TABLE 3.

TABLE 4: LIST OF MATERIALS AND APPLICATIONS

	Material “A” (core) property	Material “B” (sheath) property	Application
20	Red	Grey	Aesthetic housings
	Hard	Soft	Tactile/ergonomic devices
	Conductive	Insulating	Electronic circuits
	Transparent	Opaque	Optical devices
	Recycled	Virgin	Environmental products
25	Foam	Fiber-filled composites	Lightweight structures
	Living cells	Support media	Tissue scaffolds
	Active drugs	Protective carrier	Pharmaceuticals
	Nutrients	Food	Custom edibles
	Additive	Neat	Custom concentrates

As demonstrated herein for flow analysis of the “Compact” design, the use of finite element analysis (FEA) and computational fluid dynamics (CFD) has been used

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and is readily applicable to other F3DM system designs. The described dimensions provided herein are only representative of one application with a typical target build volume of 1 to 1000 cubic centimeters for constituent materials have viscosities between 1 and 10000 Pa s at typical processing temperatures. Scaling laws, guided by
5 modeling and analysis, may be readily applied to optimize the design of the F3DM system for different target build volumes or different constituent material properties.

Thus, the flow in FIG. 13 includes multiple operations as follows:

Processing operation 111 includes defining component geometries to produce 3-D printed components.

10 Processing operation 113 includes planning print paths for discrete materials to produce 3-D printed components.

Processing operation 115 includes mapping discrete materials to mix materials to produce 3-D printed components.

15 Processing operation 116 includes replacing extruder moves for multi-defect dispensing to produce 3-D printed components.

Processing operation 118 includes performing 3-D printing of multiple material to produce 3-D printed components.

FIG. 14 is an example diagram illustrating implementation of a printer
20 assembly to produce a 3-D printed compote according to embodiments herein.

As shown, fabrication system 1400 includes fabrication manager 140 (such as controller) and printer assembly 1. Via 3-D printing techniques, the fabrication system 1400 produces a component 200 (such as on a substrate 102) using multiple layers of material extruded from the printer assembly 1. As previously discussed, the
25 printer assembly 1 produces a respective one or more roads (extrusion layer) to include one or more materials 91, 92, 93, etc. A more detailed example of producing the respective component 200 is shown FIG. 15A and 15B.

FIG. 15A is example diagram illustrating multiple layers of extrusions from a
30 printer assembly according to embodiments herein.

In this example embodiment, the controller 140 controls the printer assembly 1 to initially apply a first road 161-1 (extrusion including multiple materials) onto the

substrate 102. In this example embodiment, the road 162-1 includes material 92 encasing the material 91.

The printer assembly 1 applies a second road 162-1 (extrusion including multiple materials) onto the substrate 102. In this example embodiment, the road
5 162-1 includes material 92 encasing the material 91.

The combination of roads 161-1, 162-1, etc., represents a first layer of material disposed on the substrate 102 to form component 200.

The controller 140 also controls the printer assembly 1 to produce additional roads (extrusions) on the first layer of roads. For example, the controller 140 operates
10 the printer assembly 1 to apply road 161-2 over the road 161-1; the controller operates the printer assembly to apply road 162-2 over the road 162-1; and so on.

In this manner, the fabrication system as discussed herein implements application of multiple layers of extrusions from the printer assembly 1 to produce the component 200.

15 In further example embodiments, the second extrusion layer (such as road 162-1 and 162-2) of the 3-D printed component is disposed on the first extrusion layer (such as road 161-1 and 161-2). In such an instance, the first extrusion layer resides between the substrate 102 and the second extrusion layer.

In one embodiment, the first extrusions 161-1 and 161-2 are disposed directly
20 on the substrate 102, the second extrusions 162-1 and 162-2 are parallel with the first extrusions 161-1 and 161-2. Alternatively, the second extrusions 162-1 and 162-2 are not parallel with the first extrusion 161-1 and 161-2.

FIG. 15B is an example diagram illustrating variations of printed components
25 according to embodiments herein.

In further example embodiments, a volumetric ratio of the first flowable material to the second flowable material in the first extrusion varies over a length of the first extrusion. For example, as in FIG. 15B, the diameter of the first flowable material varies over a length of the component 200-1. Thus, in one embodiment, a
30 diameter of the first flowable material 91 disposed in the second flowable material 92 varies over a length of the extrusion of flowable material 91.

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FIG. 16 is an example block diagram of a computer system for implementing any of the operations as previously discussed according to embodiments herein.

Note that any of the resources (such as mobile communication devices, user equipment, wireless stations, wireless base stations, communication management
5 resource, control management resource, etc.) as discussed herein can be configured to include computer processor hardware and/or corresponding executable instructions to carry out the different operations as discussed herein.

For example, as shown, computer system 1650 of the present example includes interconnect 1611 coupling computer readable storage media 1612 such as a
10 non-transitory type of media (which can be any suitable type of hardware storage medium in which digital information can be stored and or retrieved), a processor 1613 (computer processor hardware), I/O interface 1614, and a communications interface 1617.

I/O interface(s) 1614 supports connectivity to repository 1680 and input
15 resource 1692.

Computer readable storage medium 1612 can be any hardware storage device such as memory, optical storage, hard drive, floppy disk, etc. In one embodiment, the computer readable storage medium 1612 stores instructions and/or data.

As shown, computer readable storage media 1612 can be encoded with
20 management application 140-1 (e.g., including instructions) in a respective wireless station to carry out any of the operations as discussed herein.

During operation of one embodiment, processor 1613 accesses computer readable storage media 1612 via the use of interconnect 1611 in order to launch, run, execute, interpret or otherwise perform the instructions in management application
25 140-1 stored on computer readable storage medium 1612. Execution of the management application 140-1 produces management process 140-2 to carry out any of the operations and/or processes as discussed herein.

Those skilled in the art will understand that the computer system 1650 can include other processes and/or software and hardware components, such as an
30 operating system that controls allocation and use of hardware resources to execute the management application 140-1.

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In accordance with different embodiments, note that computer system may reside in any of various types of devices, including, but not limited to, a mobile computer, a personal computer system, a wireless device, a wireless access point, a base station, phone device, desktop computer, laptop, notebook, netbook computer, 5 mainframe computer system, handheld computer, workstation, network computer, application server, storage device, a consumer electronics device such as a camera, camcorder, set top box, mobile device, video game console, handheld video game device, a peripheral device such as a switch, modem, router, set-top box, content management device, handheld remote control device, any type of computing or 10 electronic device, etc. The computer system 1650 may reside at any location or can be included in any suitable resource in any network environment to implement functionality as discussed herein.

Functionality supported by the different resources will now be discussed via 15 the flowchart in FIG. 17. Note that the steps in the flowcharts below can be executed in any suitable order.

FIG. 17 is a flowchart 1700 illustrating an example method according to 20 embodiments herein. Note that there will be some overlap with respect to concepts as discussed above.

In processing operation 1710, the controller 140 controls delivery of a first flowable material 91 through a respective port 11P of a first conduit 11 into a flow combiner (a.k.a., junction 19), the flow combiner (junction 19) being operative to combine multiple types of printable materials.

25 In processing operation 1720, the controller 140 controls delivery of a second flowable material 92 through a second conduit 14 into a flow distributor 8 of the printer assembly 1, a gapped flow channel (such as associated with conical flow channel) of the flow distributor 8 feeding the second flowable material 92 into the flow combiner (junction 19).

30 In processing operation 1730, via an outlet (such as in nozzle 20N or outlet 9 associated with the junction 19) of the printer assembly 1, the controller 140 controls

dispensing of a combination of the first flowable material 91 and the second flowable material 92 received from the flow combiner (junction 19).

Note again that techniques as discussed herein are well suited for use in printer
5 heads and 3-D (3-dimensional). However, it should be noted that embodiments herein are not limited to use in such applications and that the techniques discussed herein are well suited for other applications as well.

Based on the description set forth herein, numerous specific details have been set forth to provide a thorough understanding of claimed subject matter. However, it
10 will be understood by those skilled in the art that claimed subject matter may be practiced without these specific details. In other instances, methods, apparatuses, systems, etc., that would be known by one of ordinary skill have not been described in detail so as not to obscure claimed subject matter. Some portions of the detailed description have been presented in terms of algorithms or symbolic representations of
15 operations on data bits or binary digital signals stored within a computing system memory, such as a computer memory. These algorithmic descriptions or representations are examples of techniques used by those of ordinary skill in the data processing arts to convey the substance of their work to others skilled in the art. An algorithm as described herein, and generally, is considered to be a self-consistent
20 sequence of operations or similar processing leading to a desired result. In this context, operations or processing involve physical manipulation of physical quantities. Typically, although not necessarily, such quantities may take the form of electrical or magnetic signals capable of being stored, transferred, combined, compared or otherwise manipulated. It has been convenient at times, principally for
25 reasons of common usage, to refer to such signals as bits, data, values, elements, symbols, characters, terms, numbers, numerals or the like. It should be understood, however, that all of these and similar terms are to be associated with appropriate physical quantities and are merely convenient labels. Unless specifically stated otherwise, as apparent from the following discussion, it is appreciated that throughout
30 this specification discussions utilizing terms such as "processing," "computing," "calculating," "determining" or the like refer to actions or processes of a computing platform, such as a computer or a similar electronic computing device, that

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manipulates or transforms data represented as physical electronic or magnetic quantities within memories, registers, or other information storage devices, transmission devices, or display devices of the computing platform.

While this invention has been particularly shown and described with
5 references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the present application as defined by the appended claims. Such variations are intended to be covered by the scope of this present application. As such, the foregoing description of embodiments of the present
10 application is not intended to be limiting. Rather, any limitations to the invention are presented in the following claims.

Claims

1. A printer assembly comprising:
 - 5 a first conduit operative to deliver a first flowable material through a respective port of the first conduit into a junction of the printer assembly;
 - a second conduit operative to deliver a second flowable material into a flow distributor of the printer assembly, the flow distributor comprising a flow channel to deliver the second flowable material into a gap surrounding the junction; and
 - 10 an outlet of the printer assembly operative to dispense a combination of the first flowable material and the second flowable material.
2. The printer assembly as in claim 1, wherein the gap is a circumferential gap substantially surrounding the junction to envelope the first flowable material
15 with the second flowable material as the first flowable material and the second flowable material pass through the junction.
3. The printer assembly as in claim 2 further comprising:
 - 20 a controller operative to control, over time: i) the flow rate of the first flowable material from the first conduit, and ii) the flow rate of the second flowable material from the second conduit.
4. The printer assembly as in claim 1, wherein the first conduit is operative to provide flow of the first flowable material in a first axial direction; and
25 wherein the flow distributor is operative to direct a flow of the second flowable material in multiple directions, which are different from the first axial direction.
5. The printer assembly as in claim 4, wherein the outlet of the junction extends
30 to a nozzle of the printer assembly dispensing the combination of the first flowable material and the second flowable material, the nozzle disposed in line

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with the first axial direction of the first flowable material through the first conduit.

- 5 6. The printer assembly as in claim 1, wherein a thickness of the gap is less than half the thickness of the flow channel in the distributor.
7. The printer assembly as in claim 1, wherein the flow channel of the flow distributor spirals around the gap, the spiral flow channel operative to feed the second flowable material received from the second conduit into the gap.
- 10 8. The printer assembly as in claim 7, wherein a distance between the spiral flow channel and the gap varies along a length of the spiral flow channel.
9. The printer assembly as in claim 8, wherein the flow distributor is located
- 15 between two assembled hot end body components of the printer assembly.
10. The printer assembly as in claim 1, wherein the first flowable material is a different material than the second flowable material.
- 20 11. The printer assembly as in claim 1, wherein the flow distributor is a first flow distributor, wherein the gap is located at a first junction of the first flowable material and second flowable material, the printer assembly further comprising:
 - 25 a third conduit operative to input third flowable material into a second flow distributor; and
 - wherein the second flow distributor includes a second flow channel to deliver the third flowable material into a second gap surrounding the junction, the second thinner gap operative to surround the combination of the first flowable material and the second flowable material with the third flowable
 - 30 material flowing to the outlet,
 - the outlet operative to dispense a combination of the first flowable material, the second flowable material, and the third flowable material.

12. The printer assembly as in claim 1, wherein the flow distributor includes an obstruction disposed in a path of the flow channel, around which the second flowable material flows to the gap.
- 5
13. The printer assembly as in claim 1 further comprising:
a first heater operative to heat the first flowable material conveyed through the first conduit to a first temperature; and
a second heater operative to heat the second flowable material
10 conveyed in the gapped flow channel to a second temperature.
14. A printing method comprising:
controlling delivery of a first flowable material through a respective port of a first conduit into a flow combiner of a printer assembly, the flow
15 combiner operative to combine multiple types of printable material;
controlling delivery of a second flowable material through a second conduit into a flow distributor of the printer assembly, a gapped flow channel of the flow distributor feeding the second flowable material into the flow combiner; and
20 via an outlet of the printer assembly, dispensing a combination of the first flowable material and the second flowable material received from the flow combiner.
15. The method as in claim 14 further comprising:
25 controlling a temperature and pressure of the first flowable material;
and
controlling a temperature and pressure of the second flowable material.
16. The method as in claim 14 further comprising:
30 via the outlet, dispensing a combination of the first flowable material substantially surrounded by the second flowable material.

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17. The method as in claim 14 further comprising:
via a controller, over time, controlling a volumetric ratio of: i) the input
flow rate of the first flowable material into the first conduit, and ii) the input
flow rate of the second flowable material into the second conduit.
- 5
18. The method as in claim 14, wherein the first flowable material differs in
material composition from the second flowable material.
19. The method as in claim 14, wherein the flow distributor is a first flow
10 distributor, wherein the gapped flow channel is a first gapped flow channel,
the method further comprising:
via a third conduit, inputting a third flowable material into a second
flow distributor of the printer assembly;
wherein the second flow distributor includes at least one flow channel
15 disposed around a second thinner gapped flow channel operative to surround
the combination of the first flowable material and the second flowable
material with the third flowable material; and
via the outlet dispensing a combination of the first flowable material,
the second flowable material, and the third flowable material.
- 20
20. The method as in claim 14, wherein the volumetric ratio of the first flowable
material to the second flowable material in an extrusion from the outlet of the
flow combiner varies from 0 to 100 percent.
- 25
21. A manufactured component fabricated via the method of claim 14, the
manufactured component comprising:
one or more extrudates, wherein the extrudates comprise an inner
material and outer material, and a composition of the inner material and outer
material constituting the extrudates varying as a function of the extrudate
30 position.
22. A printed component comprising:

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the combination of the first flowable material and the second flowable material as in claim 1, the combination of the first flowable material and the second flowable material dispensed from the outlet of the printer assembly, wherein the material dispensed forms one or more extrudates deposited on a substrate,

wherein the extrudates comprise an inner material and outer material, and a composition of the inner material and outer material constituting the extrudates varying as a function of the extrudate position.

23. The printed component of claim 22, wherein the first flowable material differs in material composition to the second flowable material.

24. Computer-readable storage hardware having instructions stored thereon, the instructions, when carried out by computer processor hardware, cause the computer processor hardware to:

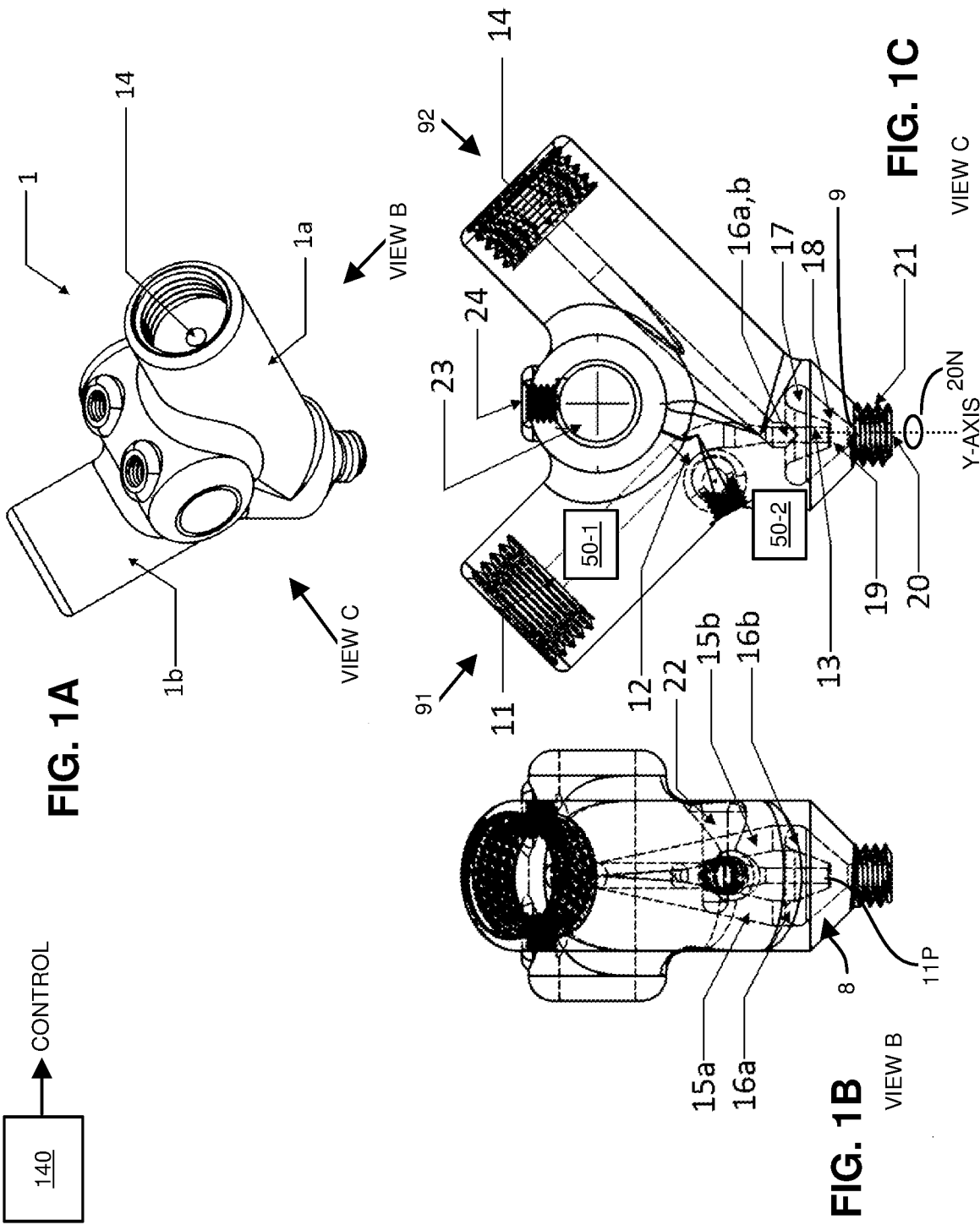
control delivery of a first flowable material through a respective port of a first conduit into a flow combiner of a printer assembly, the flow combiner operative to combine multiple types of printable material;

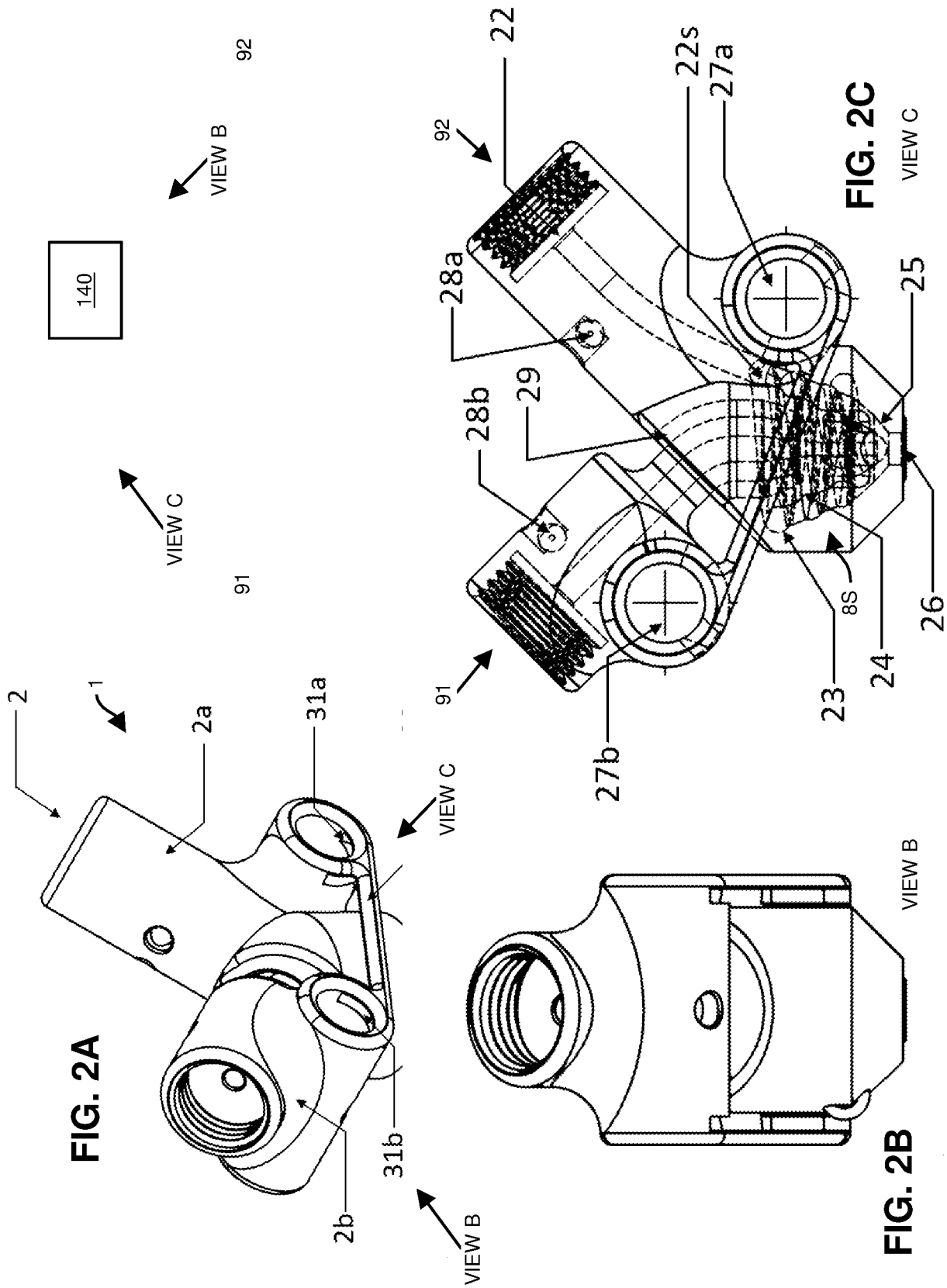
control delivery of a second flowable material through a second conduit into a flow distributor of the printer assembly, a gapped flow channel of the flow distributor feeding the second flowable material into the flow combiner; and

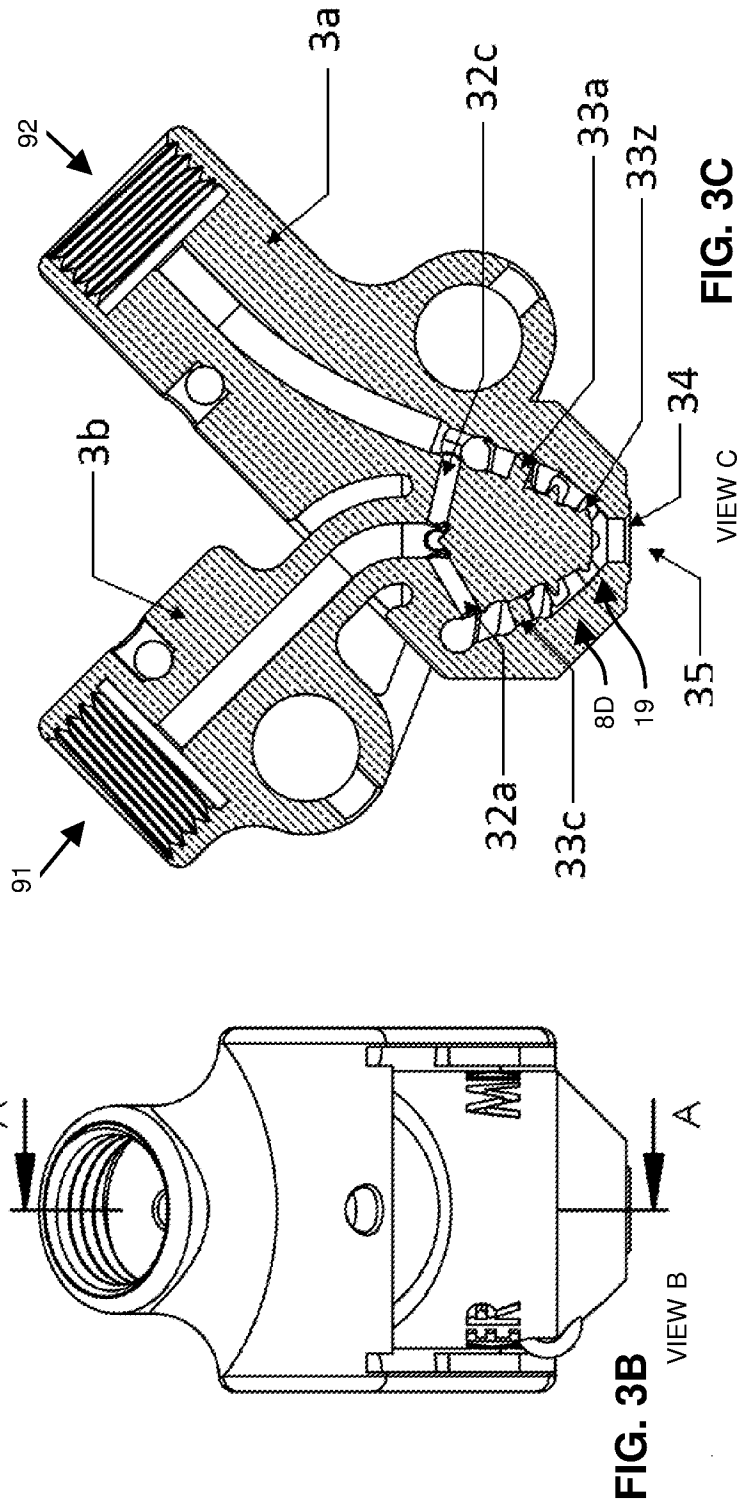
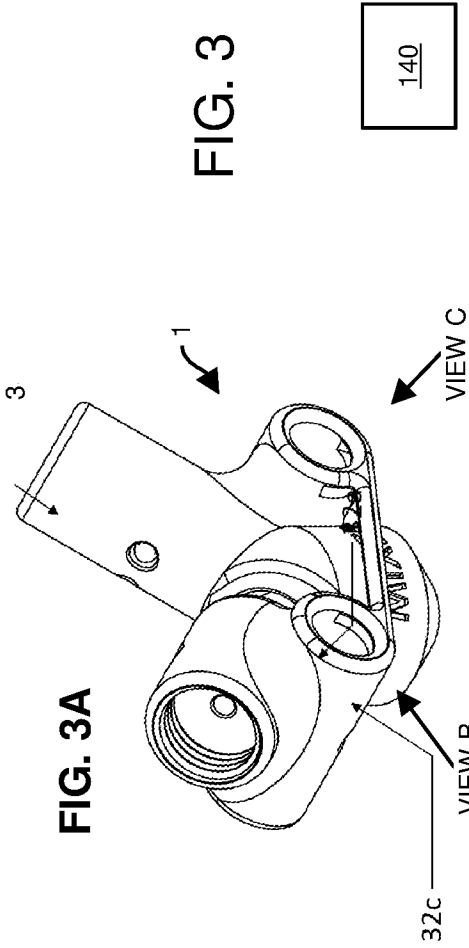
via an outlet of the printer assembly, control dispensing of a combination of the first flowable material and the second flowable material received from the flow combiner.

25. An apparatus comprising:
a substrate; and
a first printed road disposed on the substrate, the first printed road comprising first flowable material and second flowable material dispensed as a first extrusion from a 3D printer assembly onto the substrate, the second flowable material enveloping the first flowable material in the first extrusion.

26. The apparatus as in claim 25, wherein the first printed road on the substrate comprises the first flowable material enveloped by the second flowable material.
- 5
27. The apparatus as in claim 25 further comprising:
a second printed road, the second printed road comprising the first flowable material and the second flowable material dispensed as a second extrusion from the 3D printer assembly, the second flowable material enveloping the first flowable material in the second extrusion.
- 10
28. The apparatus as in claim 26, wherein the second extrusion is disposed on the first extrusion in which the first extrusion resides between the substrate and the second extrusion.
- 15
29. The apparatus as in claim 27, wherein second extrusion is disposed on the substrate, the second extrusion being parallel with the first extrusion.
30. The apparatus as in claim 27, wherein the second extrusion is not parallel with the first extrusion.
- 20
31. The apparatus as in claim 25, wherein a volumetric ratio of the first flowable material to the second flowable material in the first extrusion varies over a length of the first extrusion.
- 25
32. The apparatus as in claim 25, wherein a diameter of the first flowable material disposed in the second flowable material varies over a length of the first extrusion.
- 30
33. The apparatus as in claim 31, wherein a diameter of the second flowable material in the first extrusion varies over a length of the first extrusion.







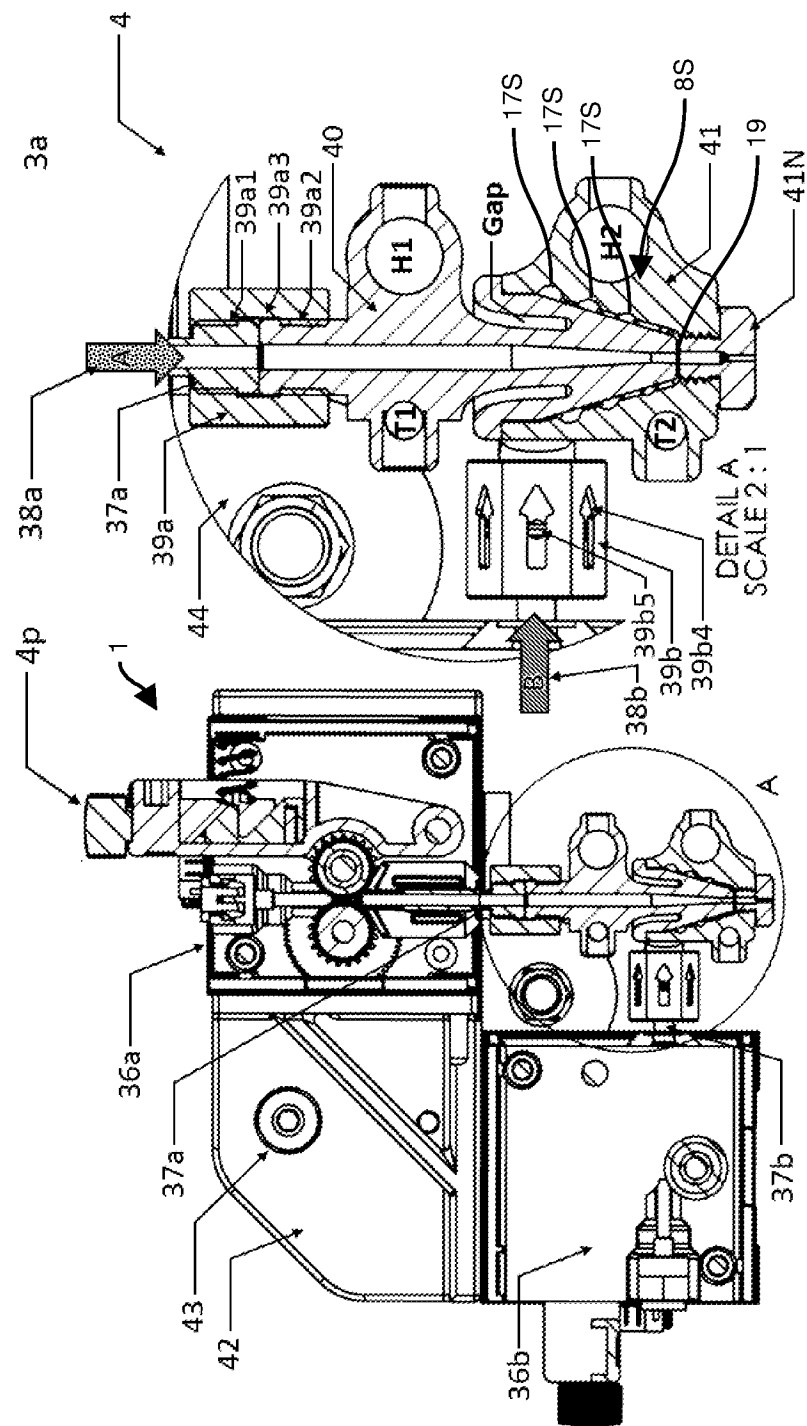
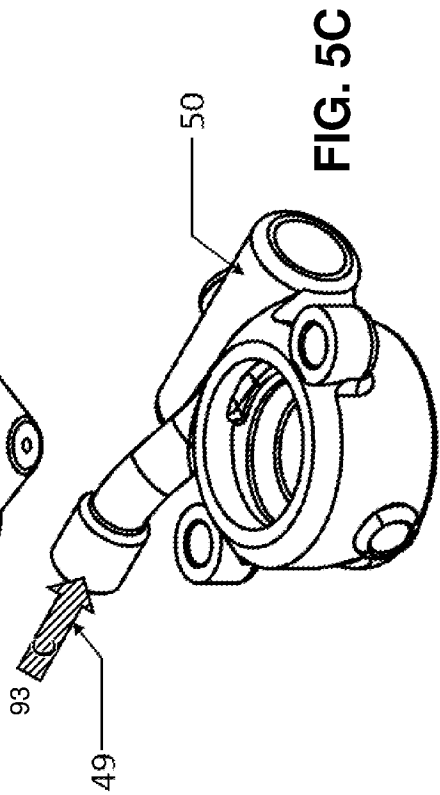
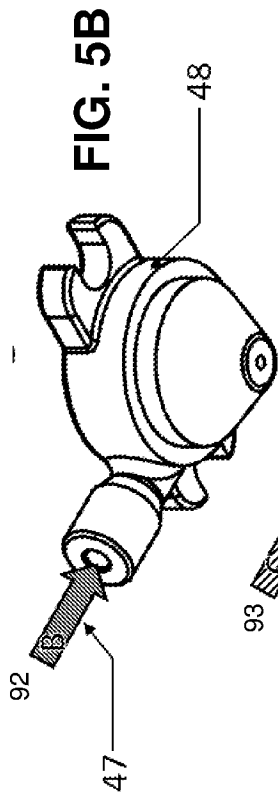
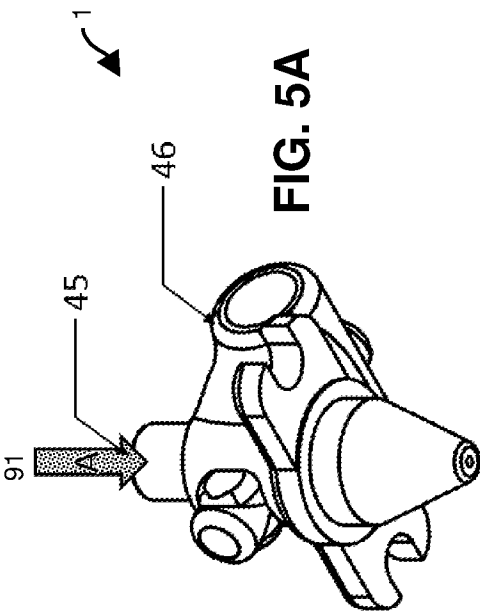
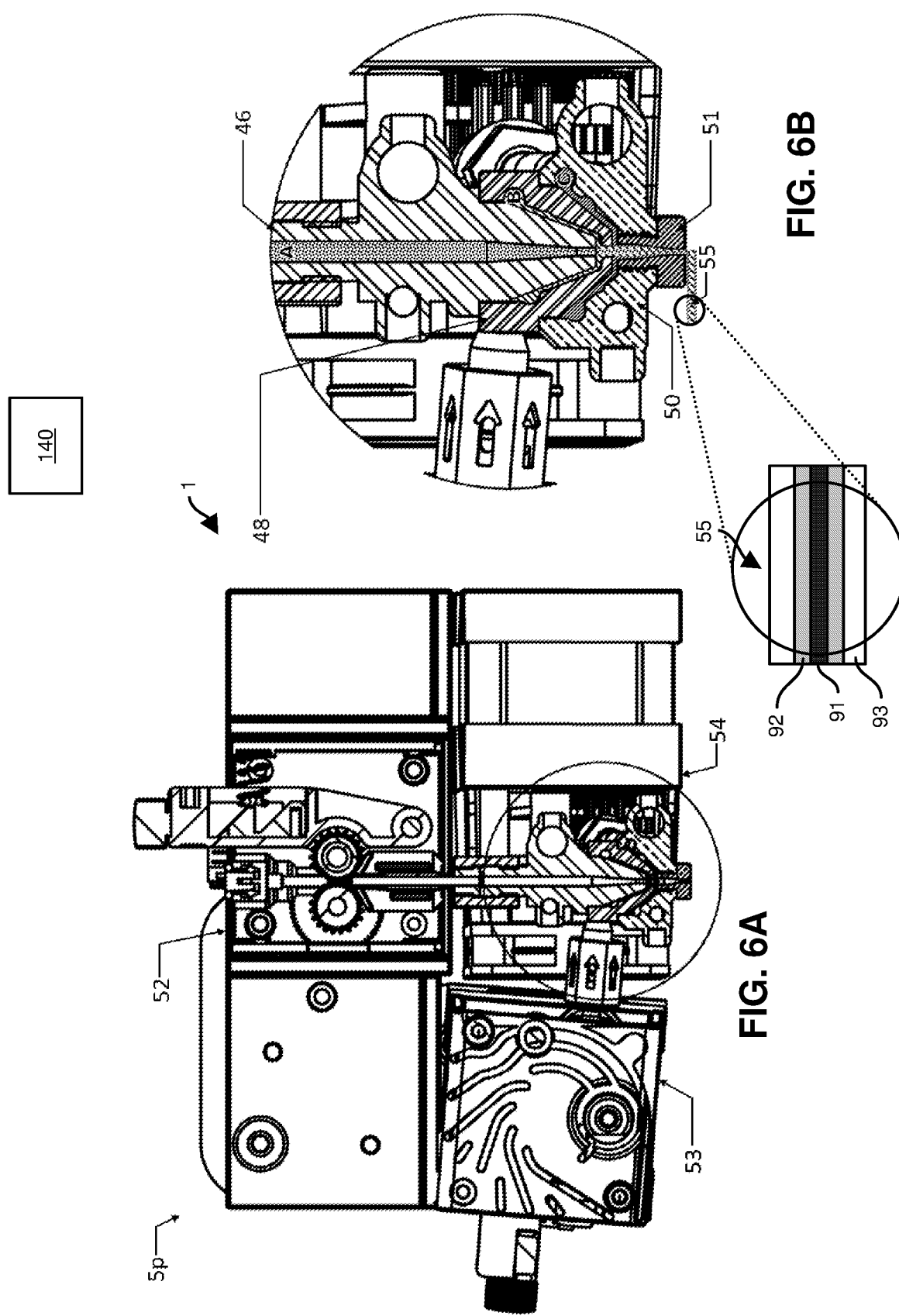


FIG. 4B

FIG. 4A

140





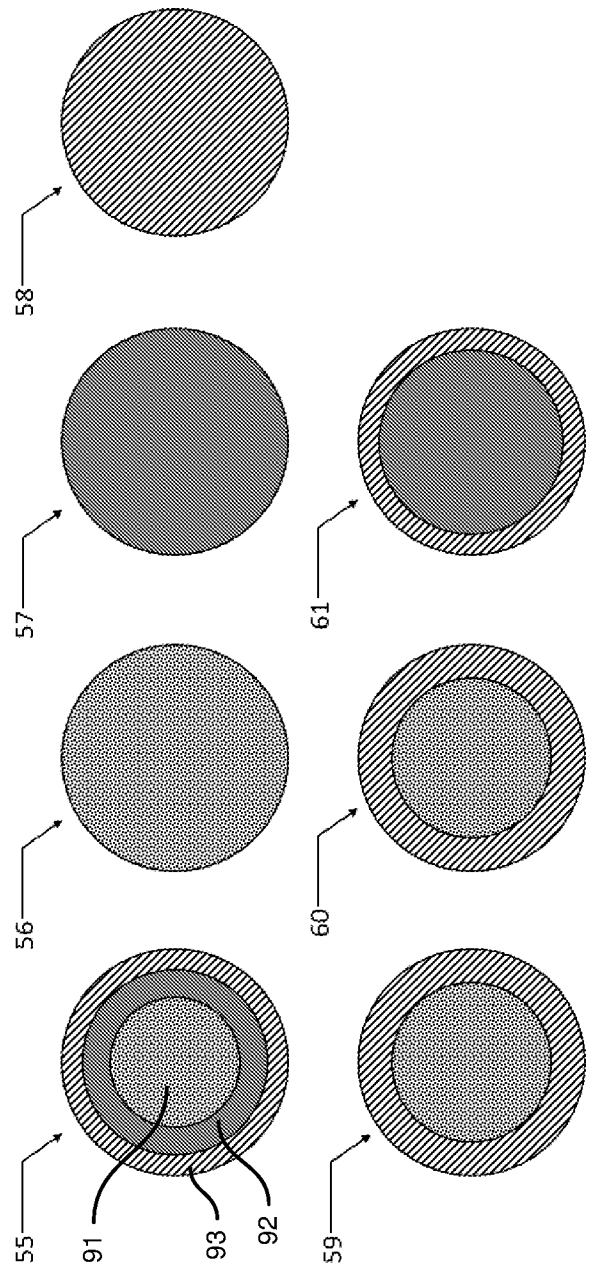
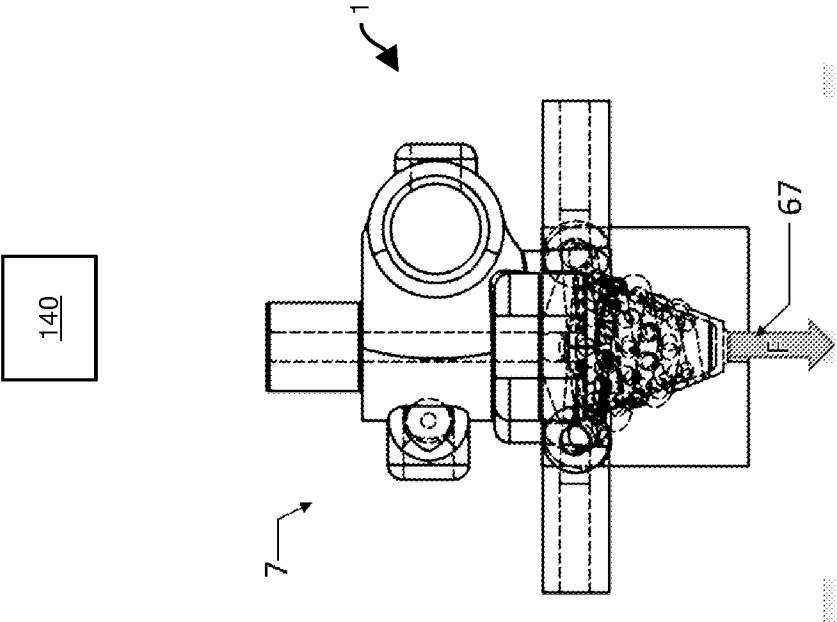
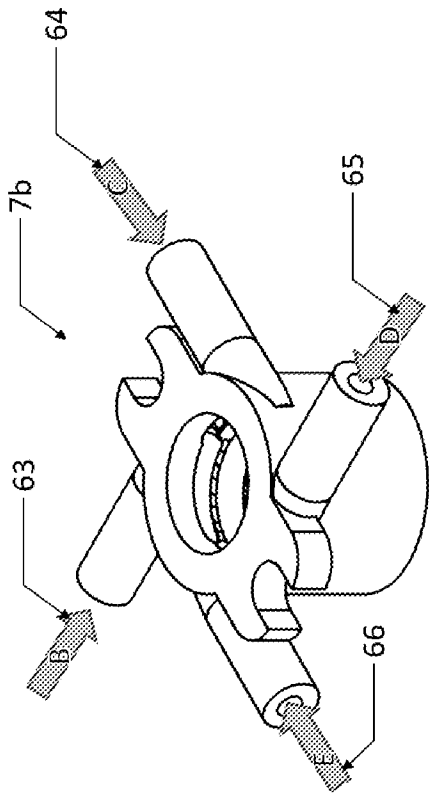
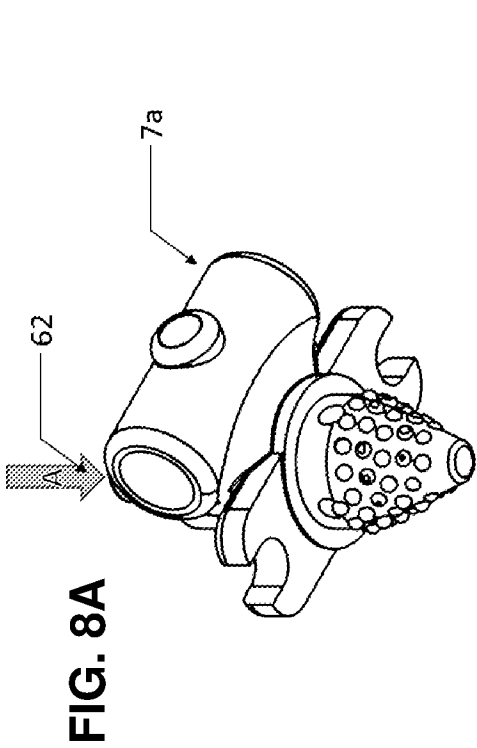


FIG. 7



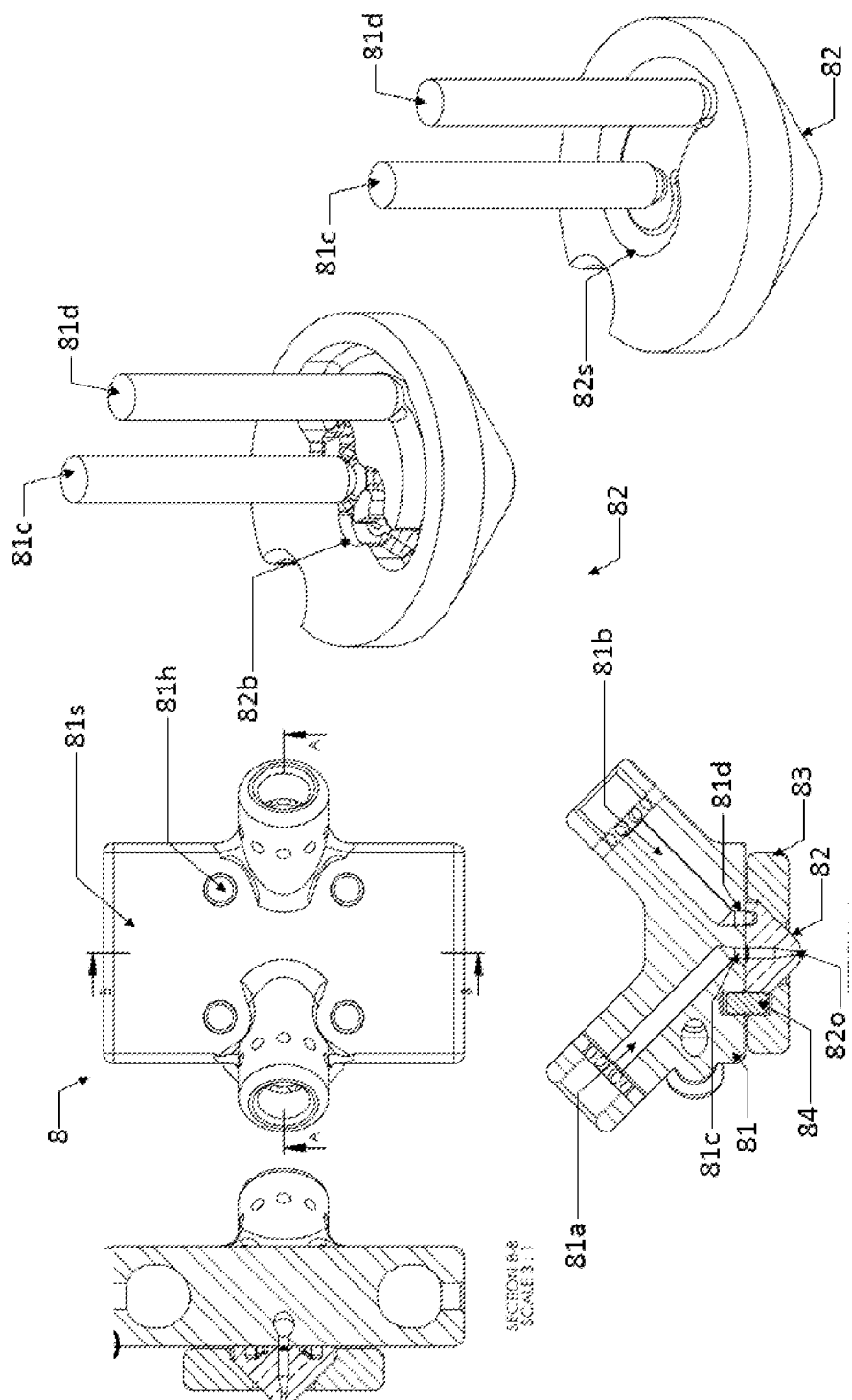
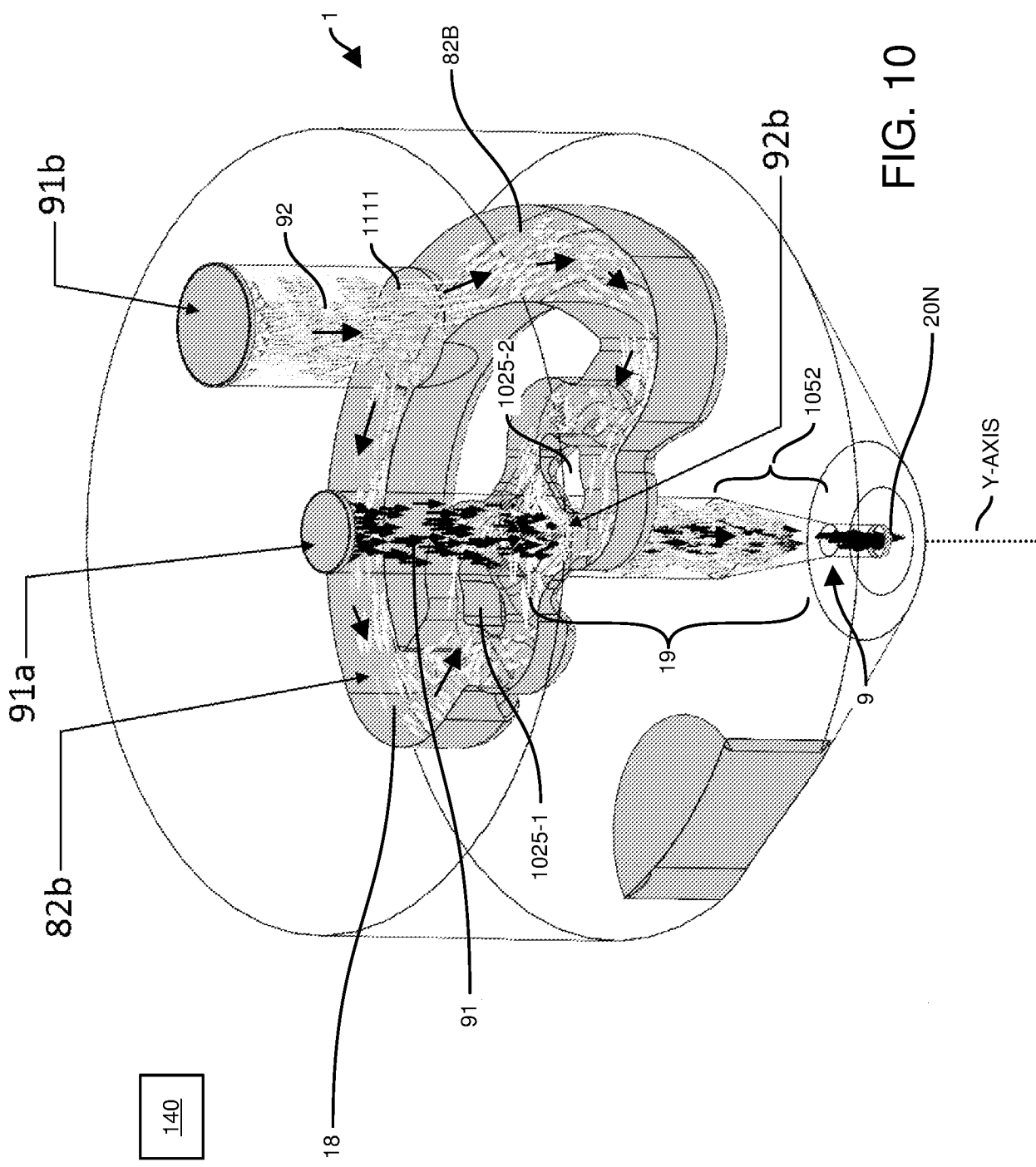


FIG. 9



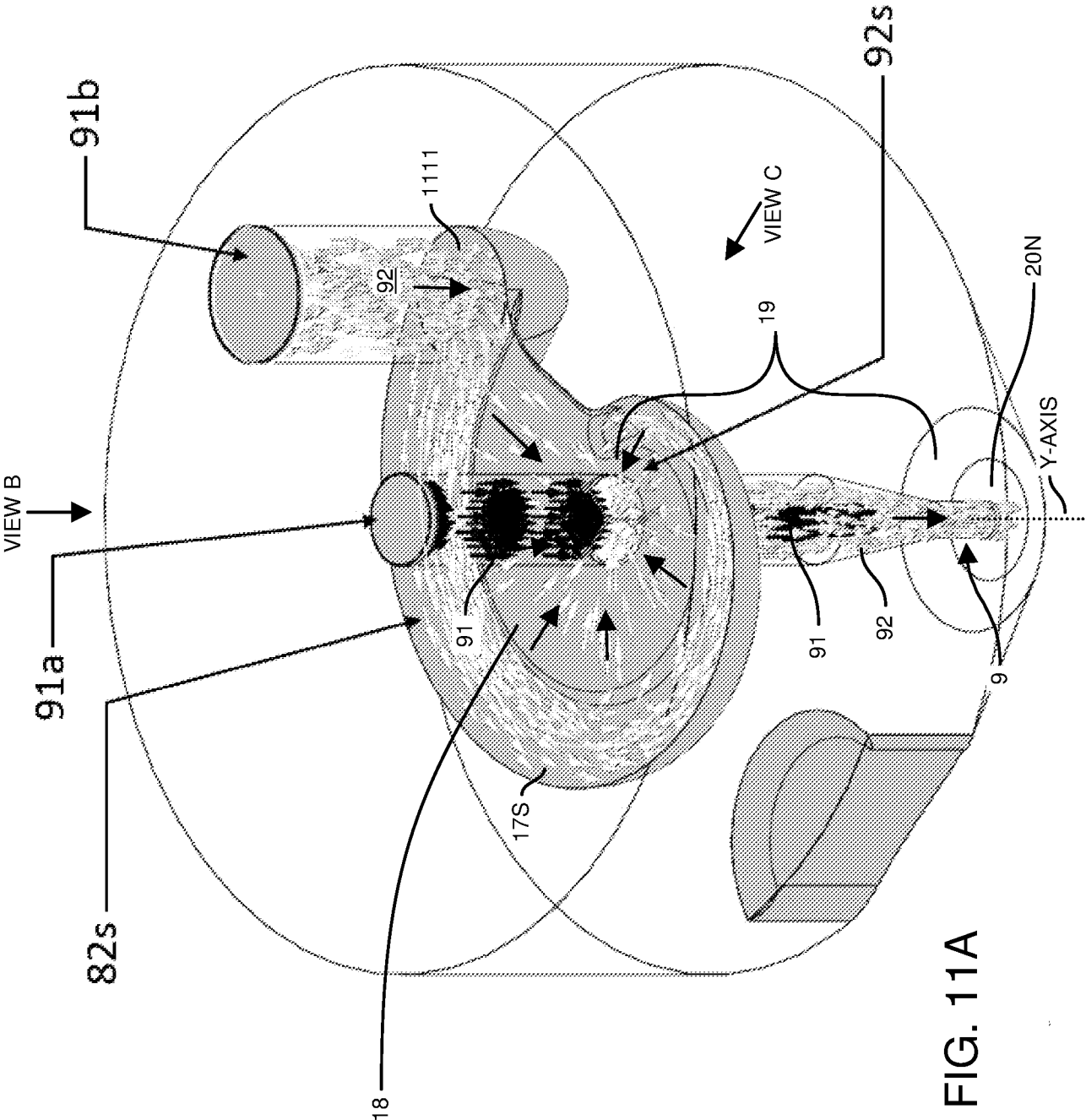


FIG. 11B

TOP
VIEW B

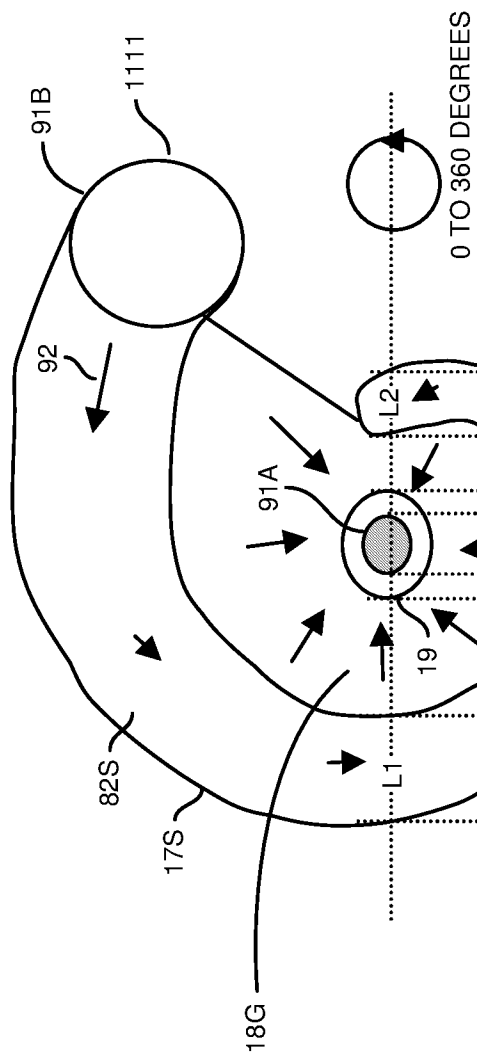
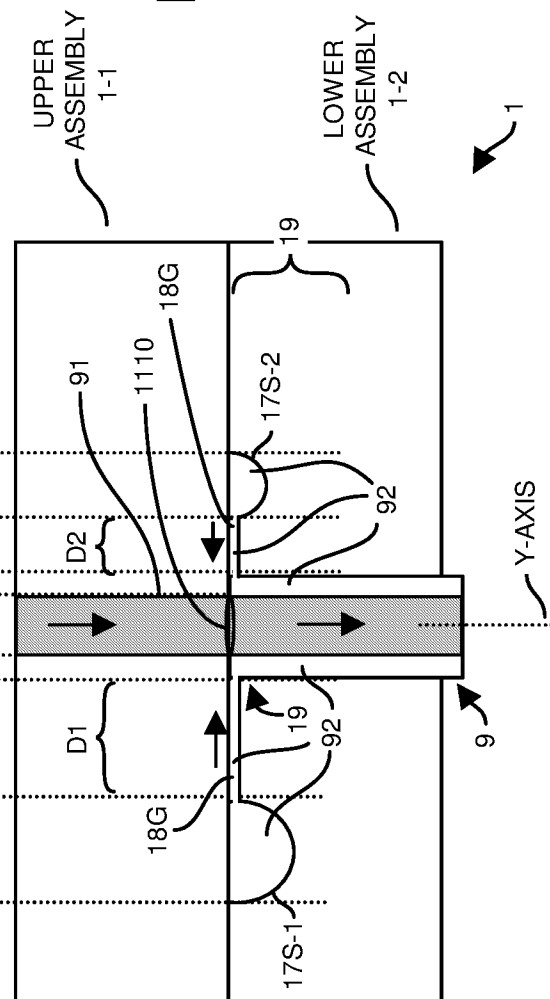


FIG. 11C

SIDE
VIEW C



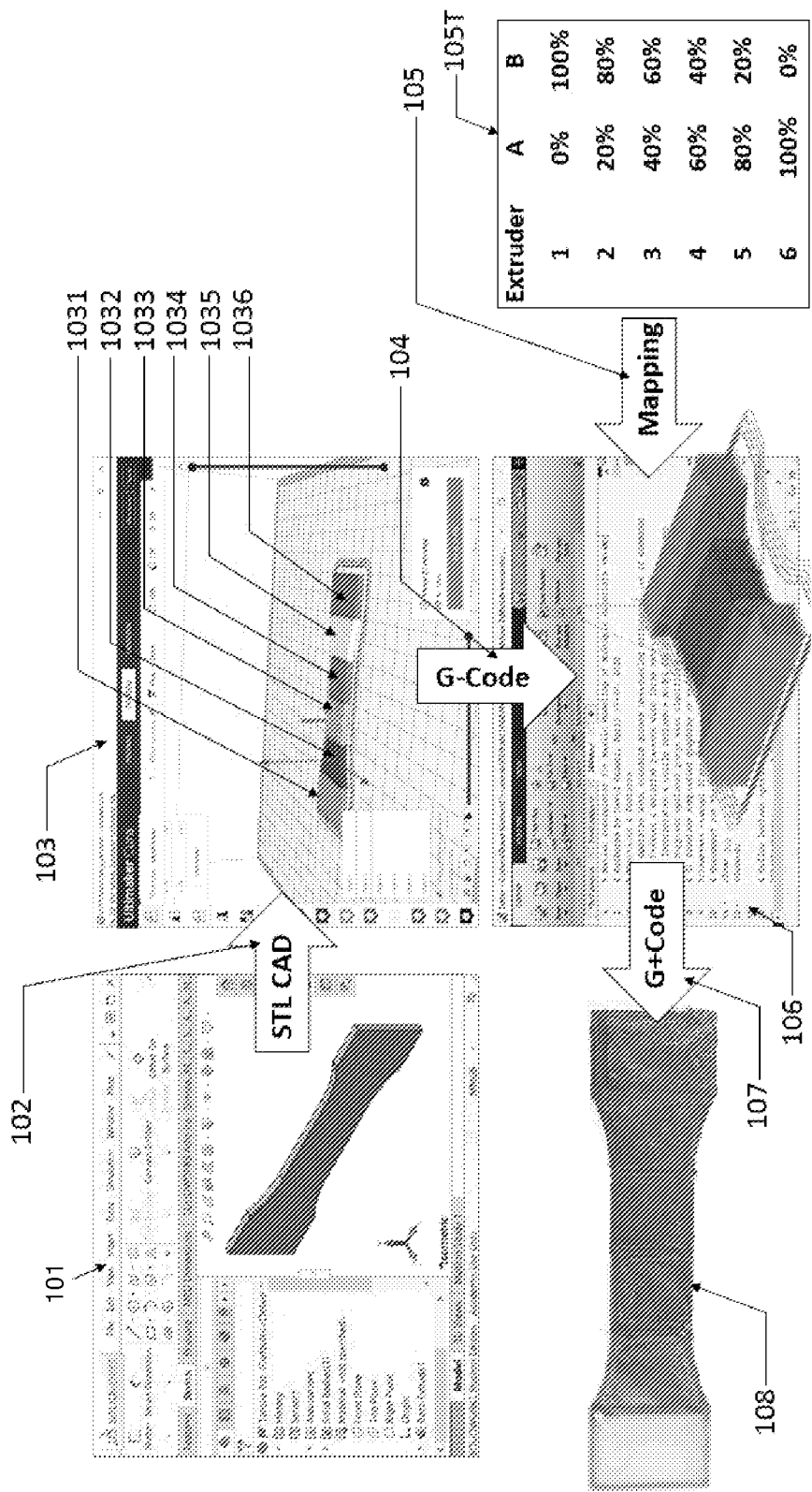


FIG. 12

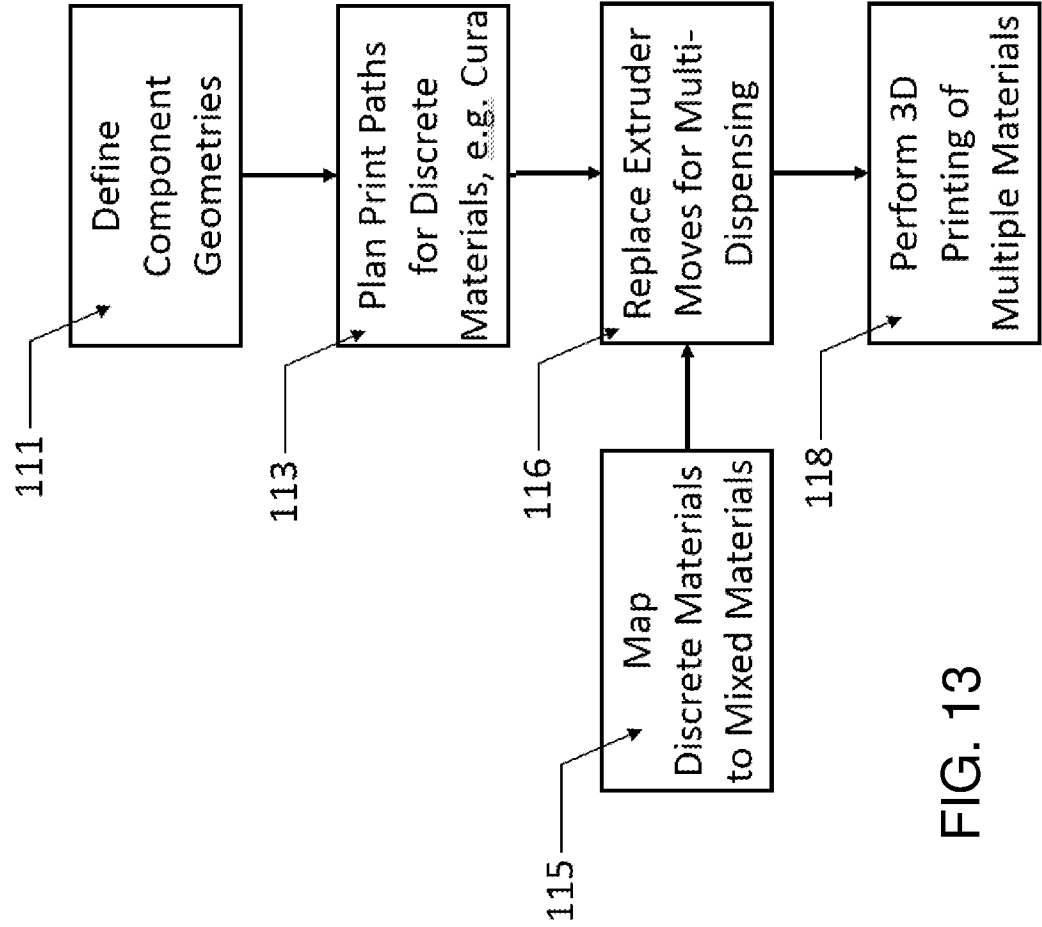
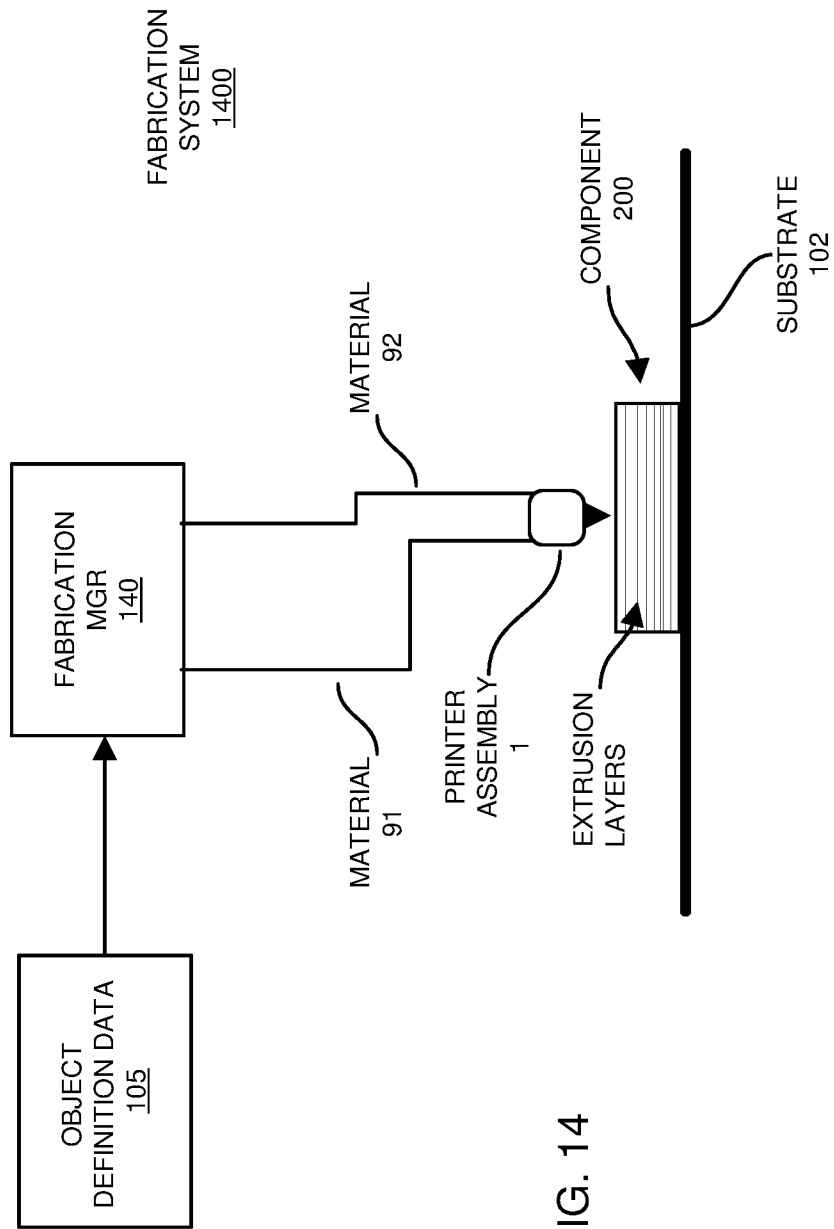


FIG. 13



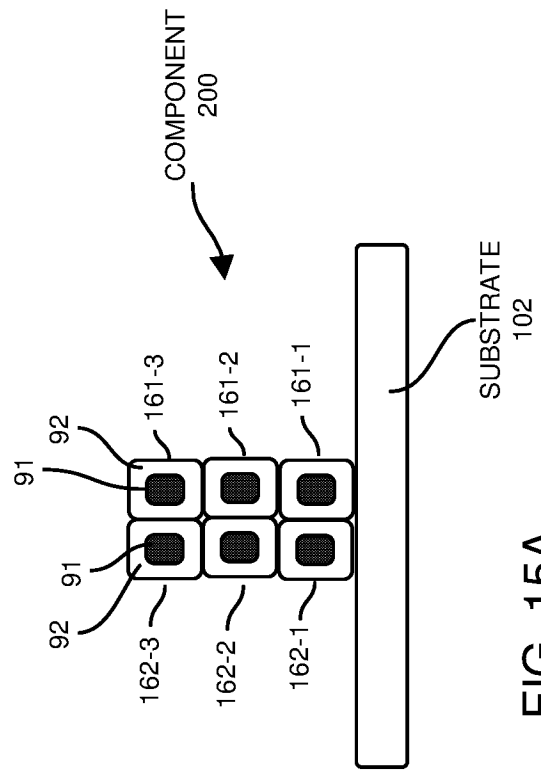
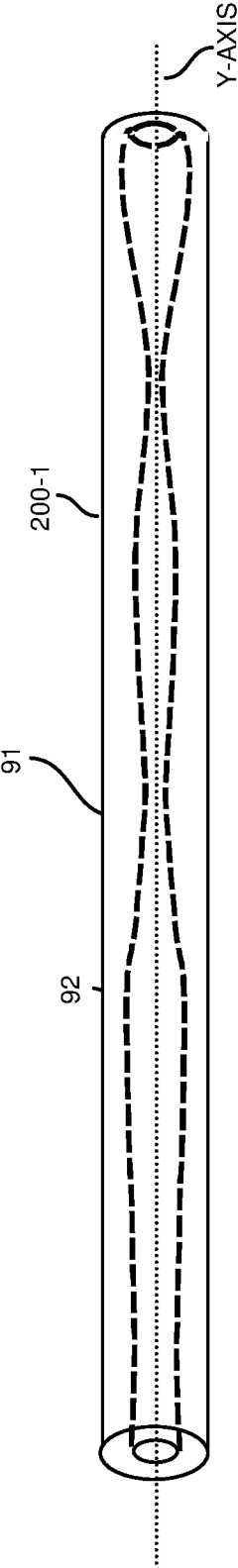


FIG. 15A

FIG. 15B



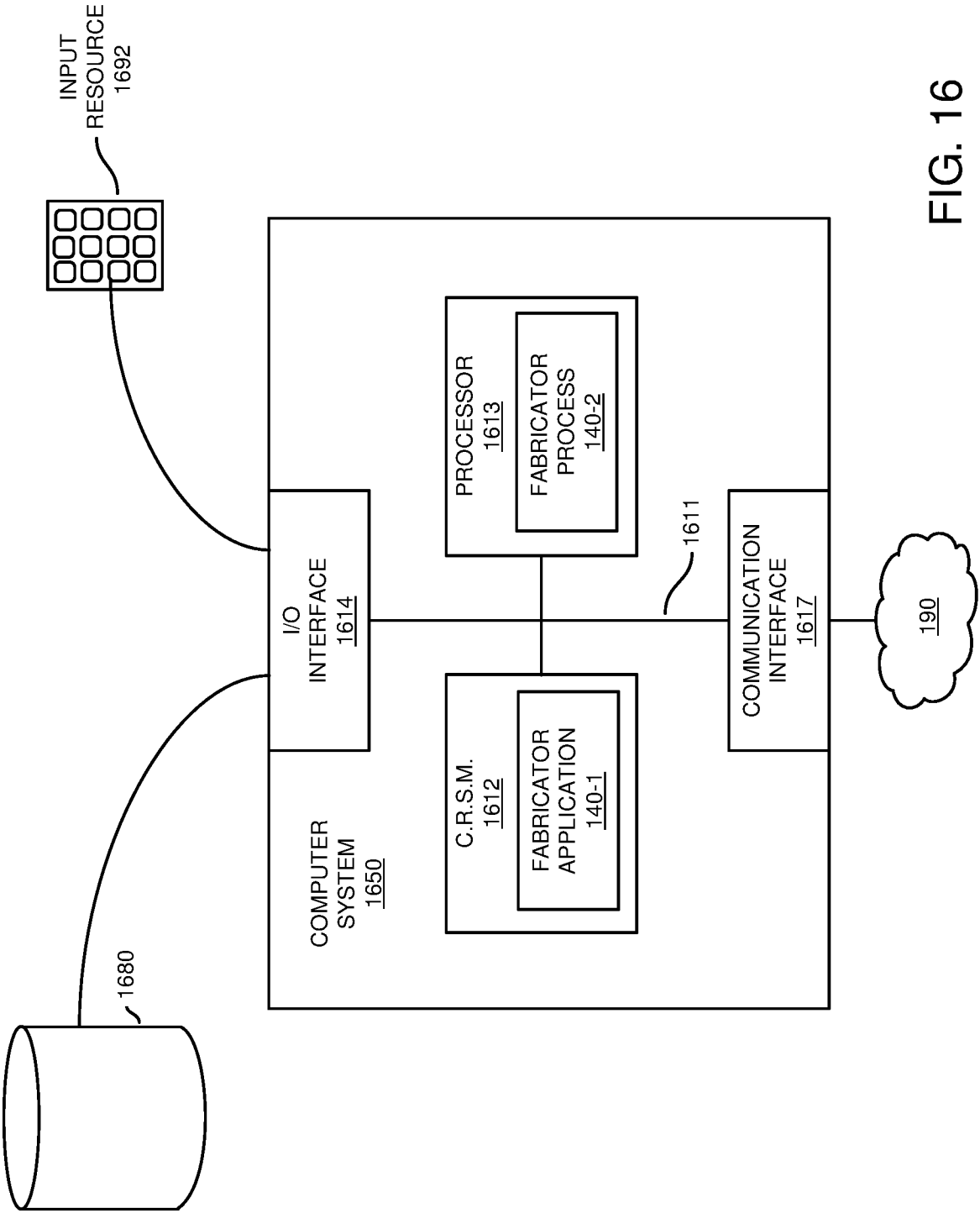


FIG. 16

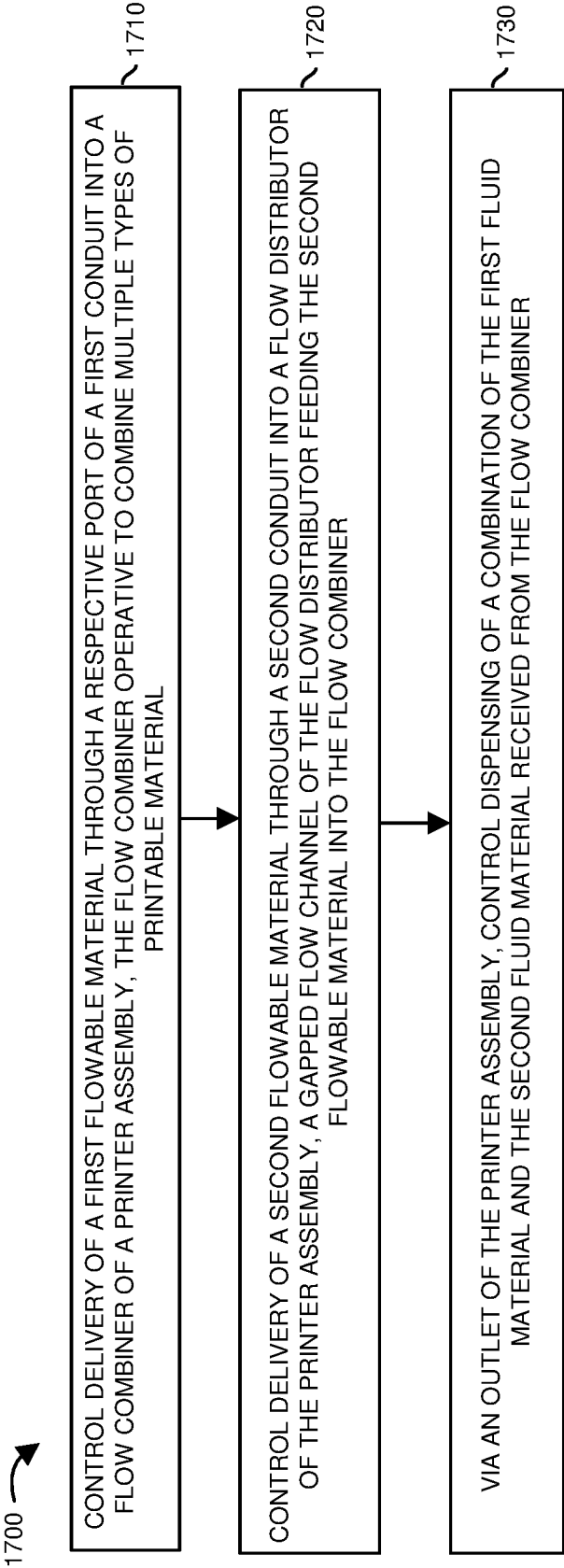


FIG. 17