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Batchelder et al.

(54) **ENCODED CONSUMABLE MATERIALS AND SENSOR ASSEMBLIES FOR USE IN ADDITIVE MANUFACTURING SYSTEMS**

(71) Applicant: **Stratasys, Inc.**, Eden Prairie, MN (US)

(72) Inventors: **J. Samuel Batchelder**, Somers, NY (US); **Michael D. Bosveld**, Bloomington, MN (US)

(73) Assignee: **Stratasys, Inc.**, Eden Prairie, MN (US)

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Publication Classification

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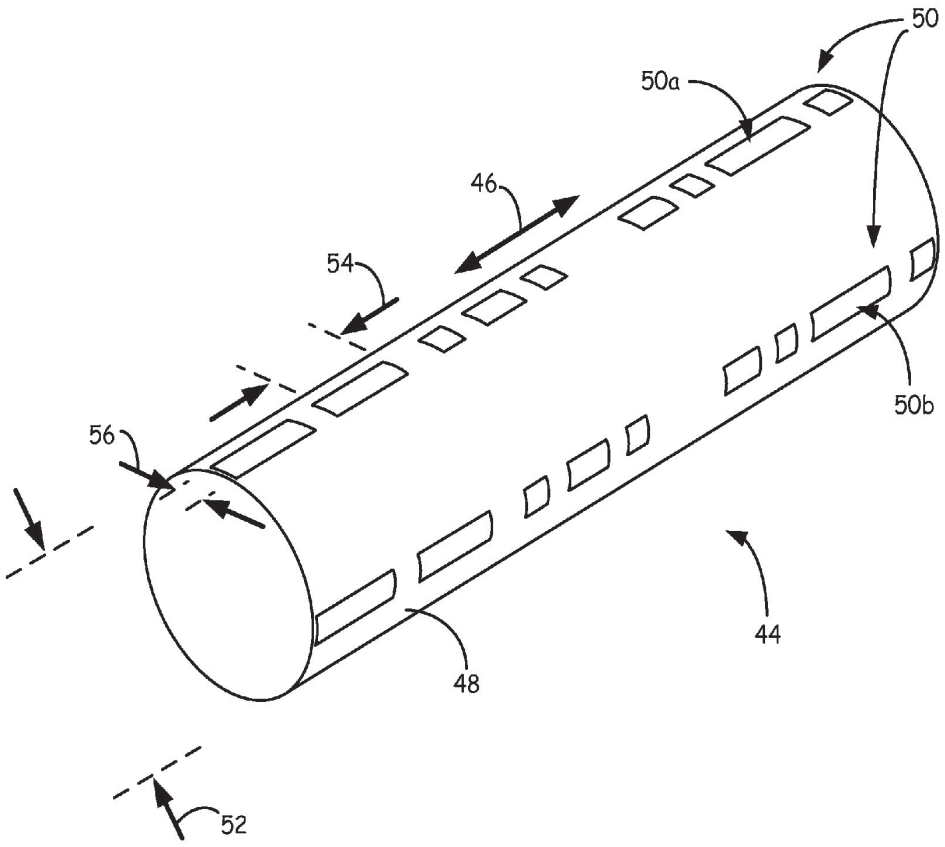
(52) **U.S. Cl.**

CPC ***B29B 11/14*** (2013.01); ***B29C 67/0085*** (2013.01); ***B29C 67/0088*** (2013.01)

USPC **428/542.8**; 264/40.1

(57) **ABSTRACT**

A consumable material and sensor assembly for use in an additive manufacturing system, the consumable material comprising an exterior surface having encoded markings that are configured to be read by the sensor assembly, where the consumable material is configured to be consumed in the additive manufacturing system to build at least a portion of a three-dimensional model.



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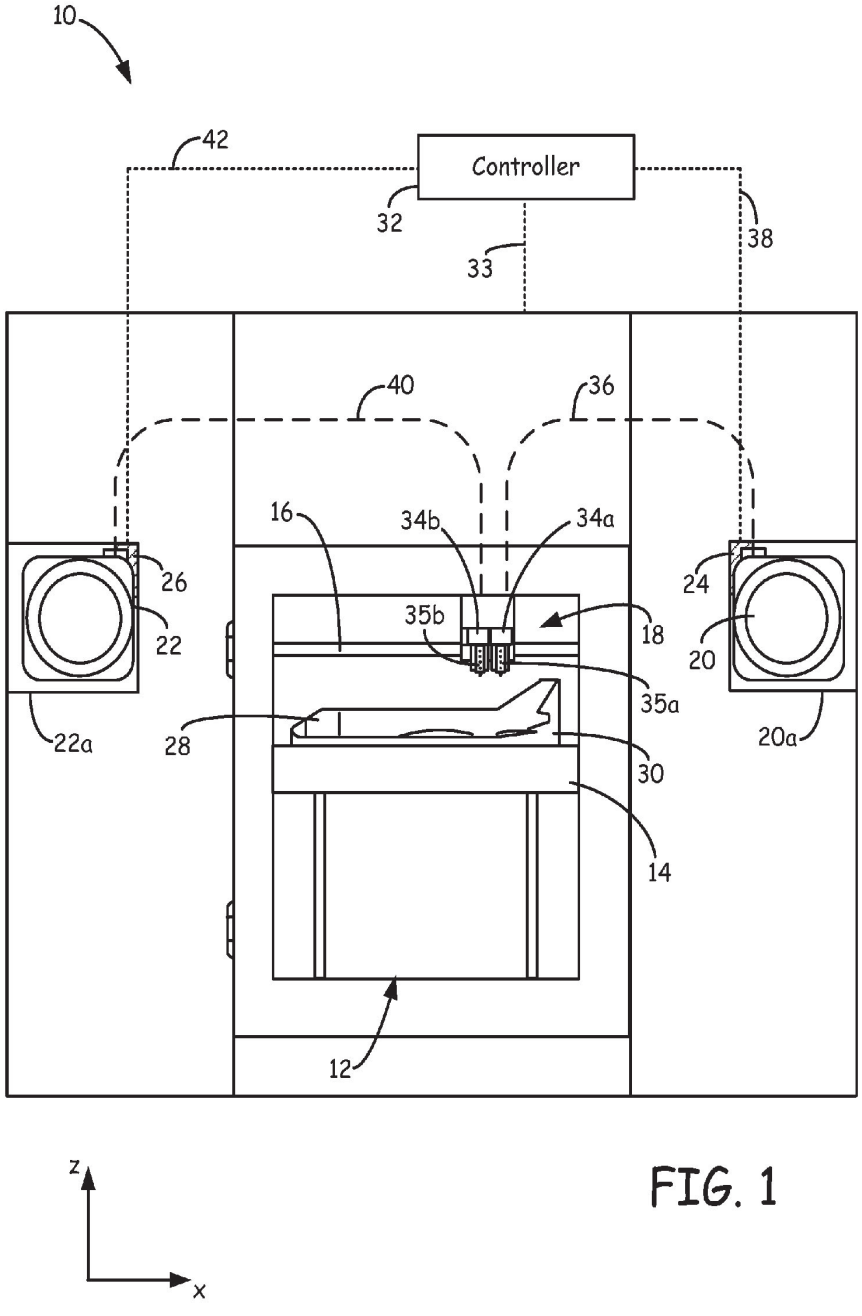

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FIG. 1

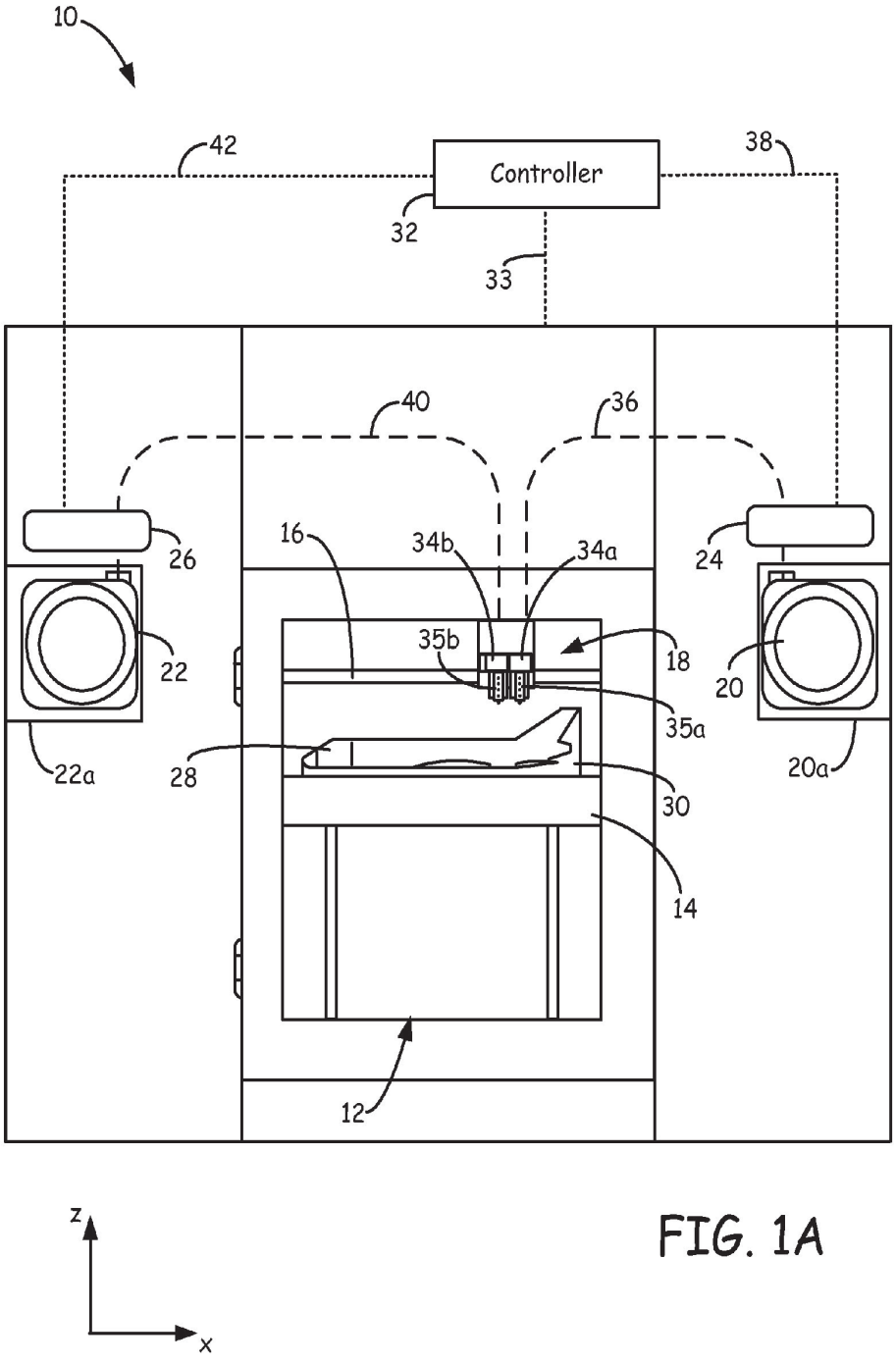
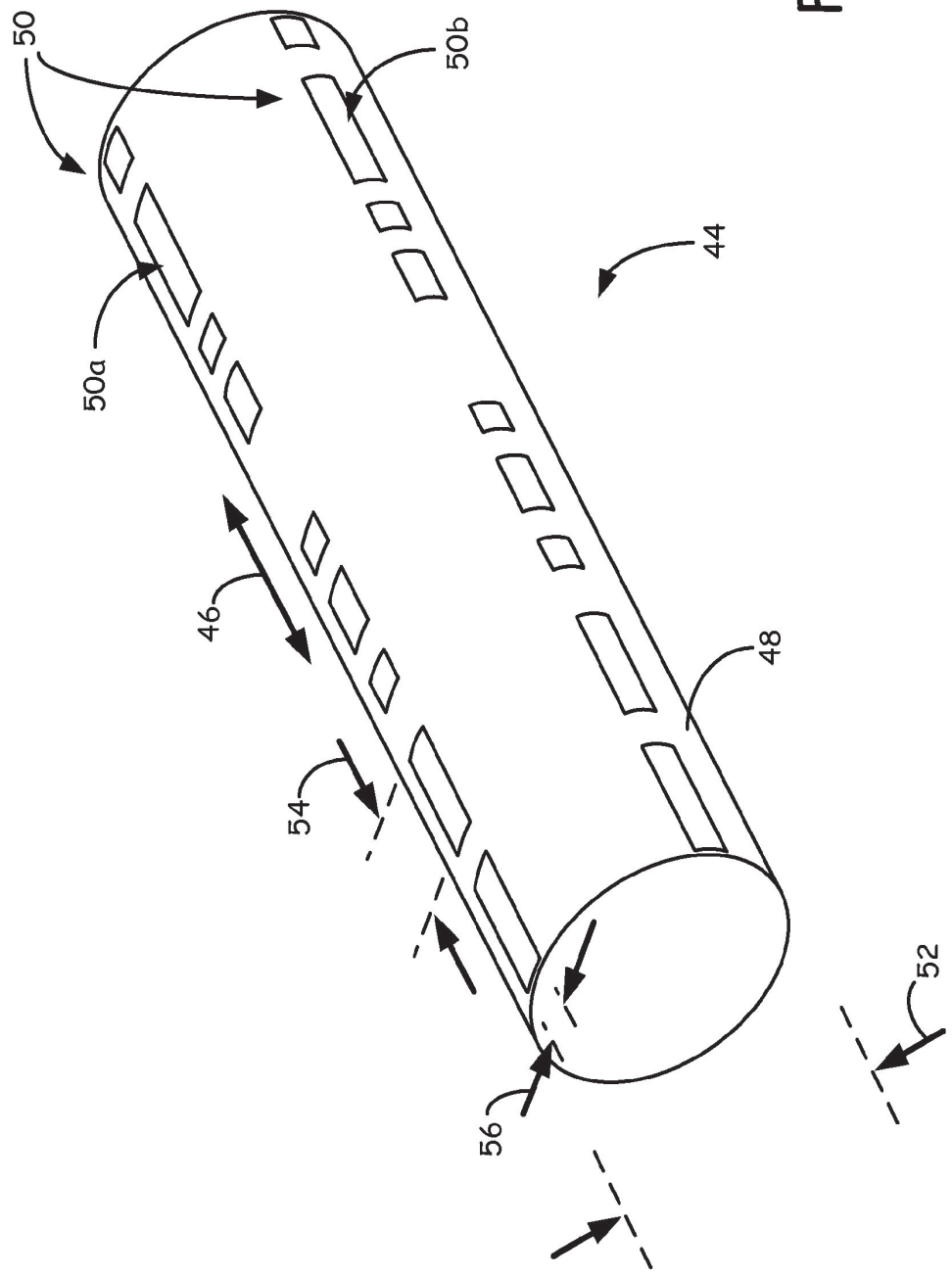

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FIG. 1A

FIG. 2



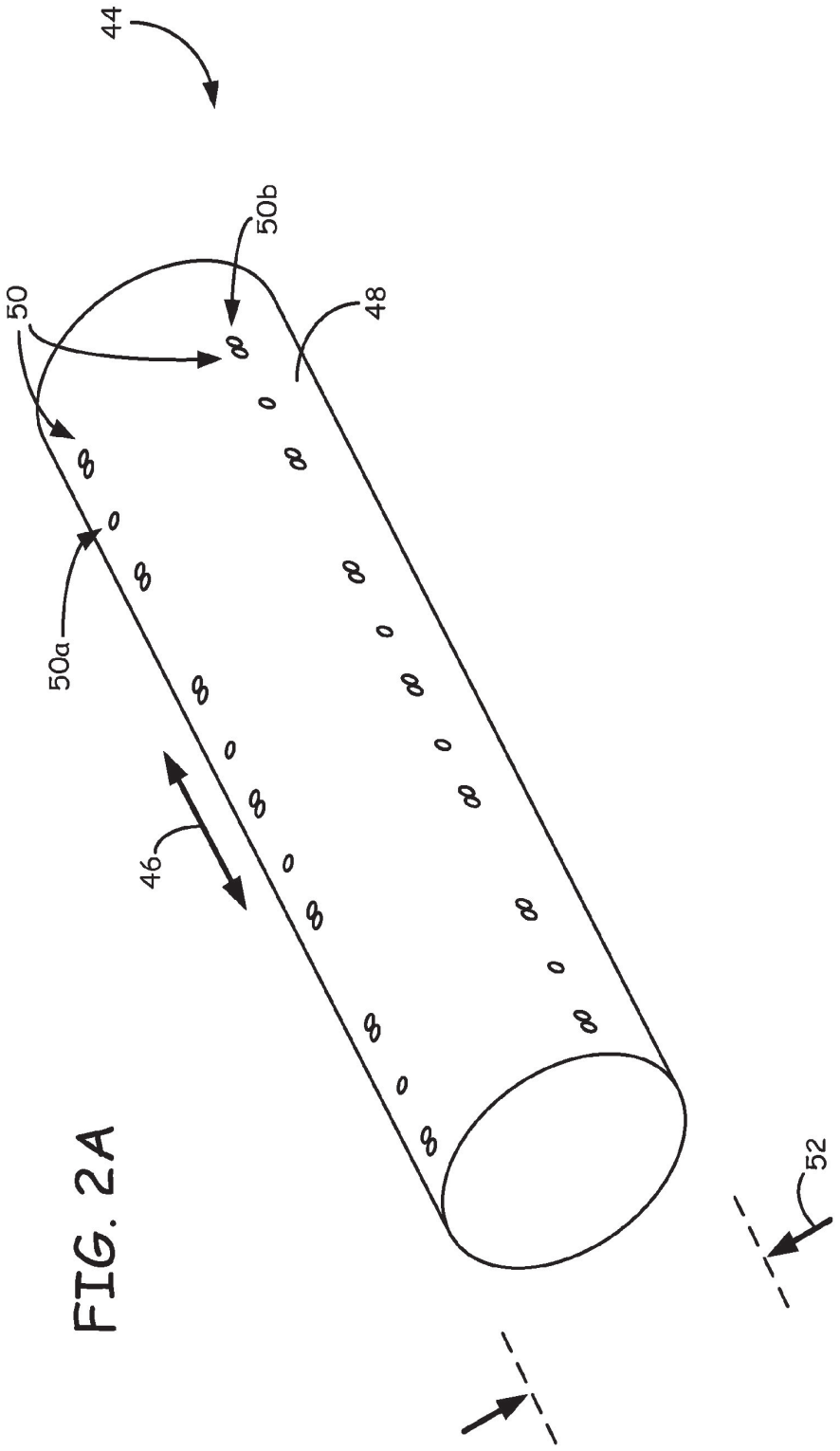


FIG. 2A

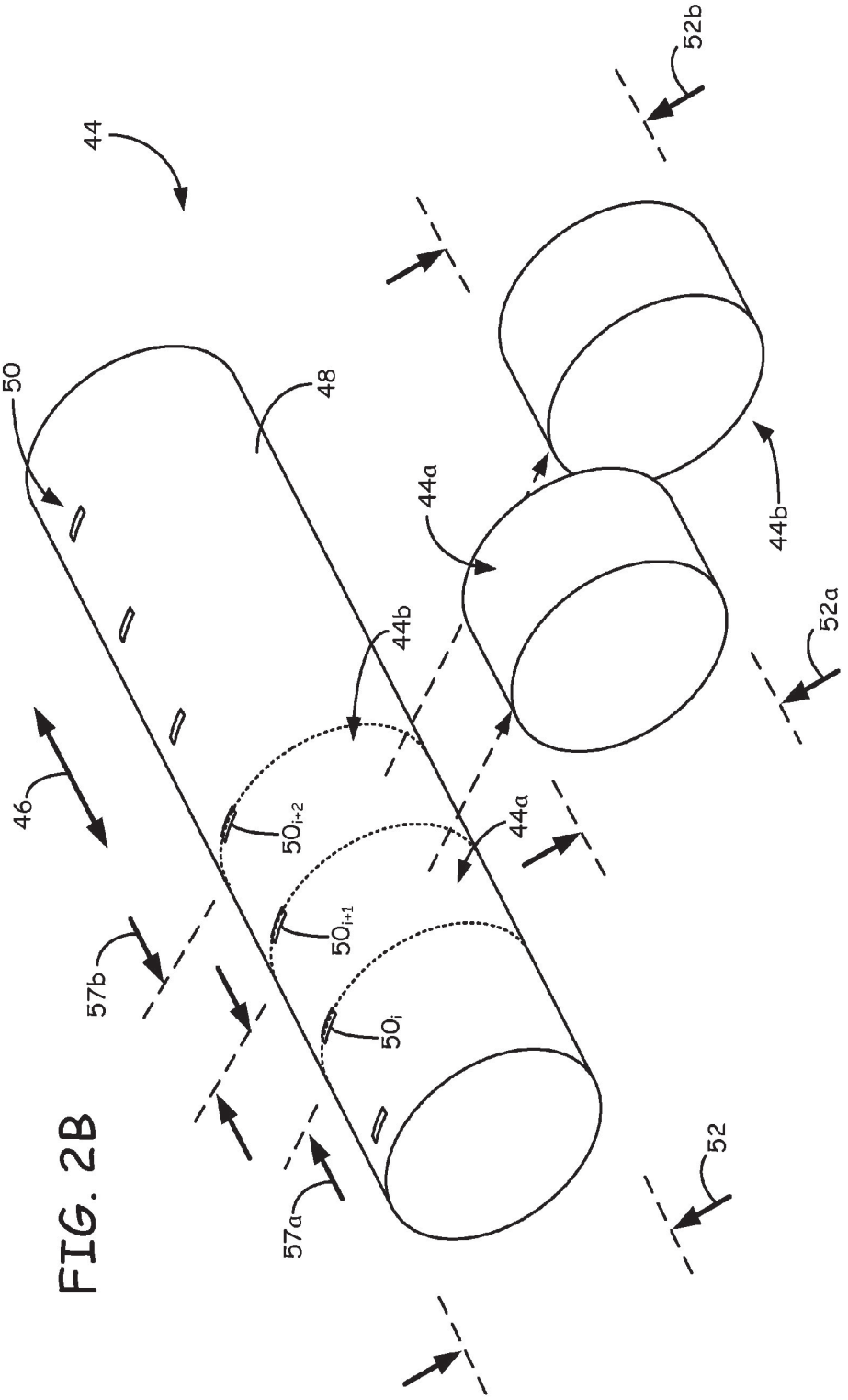


FIG. 2B

FIG. 3

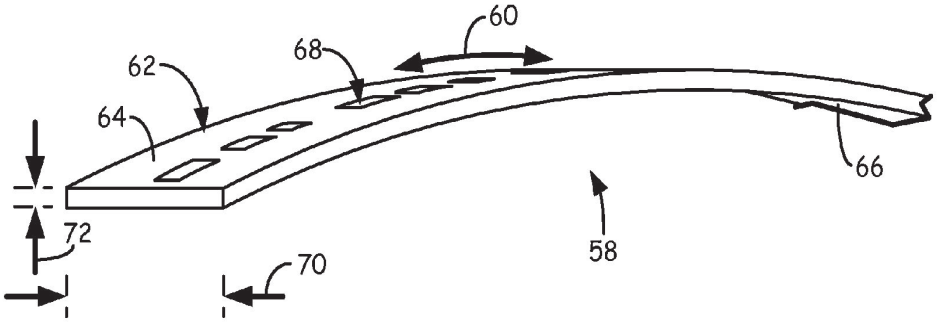
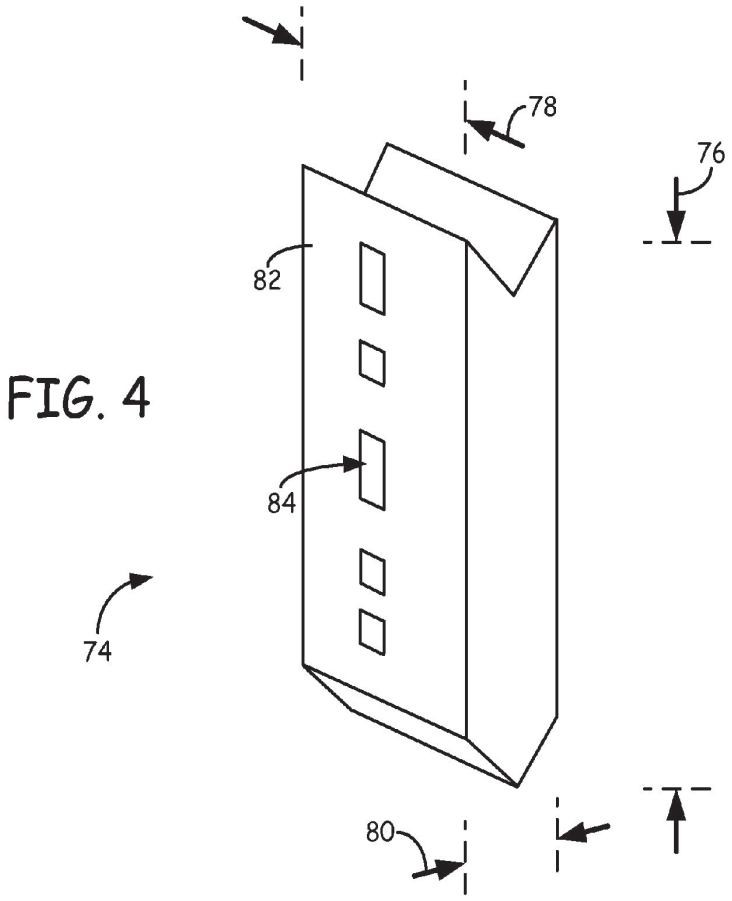


FIG. 4



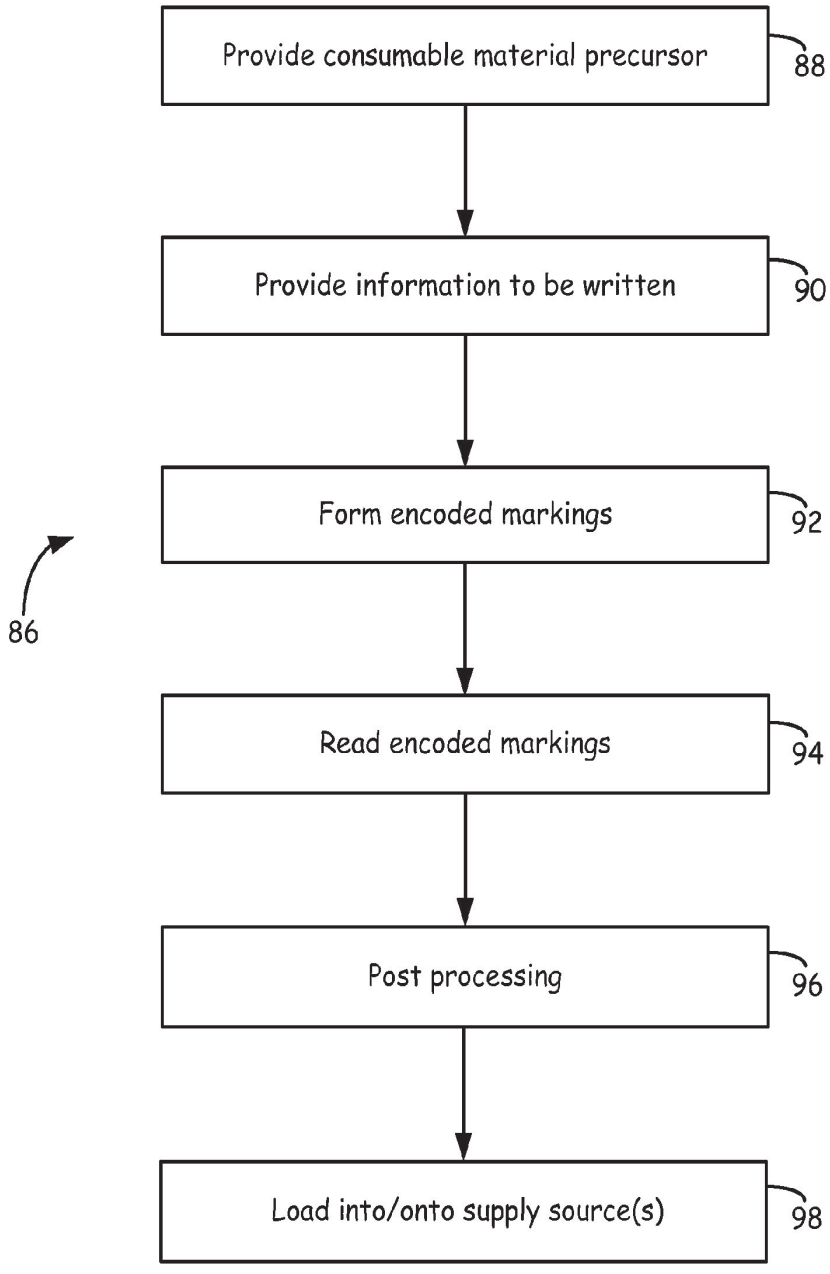

Provide consumable material precursor
88
Provide information to be written
90
Form encoded markings
92
86
Read encoded markings
94
Post processing
96
Load into/onto supply source(s)
98

FIG. 5

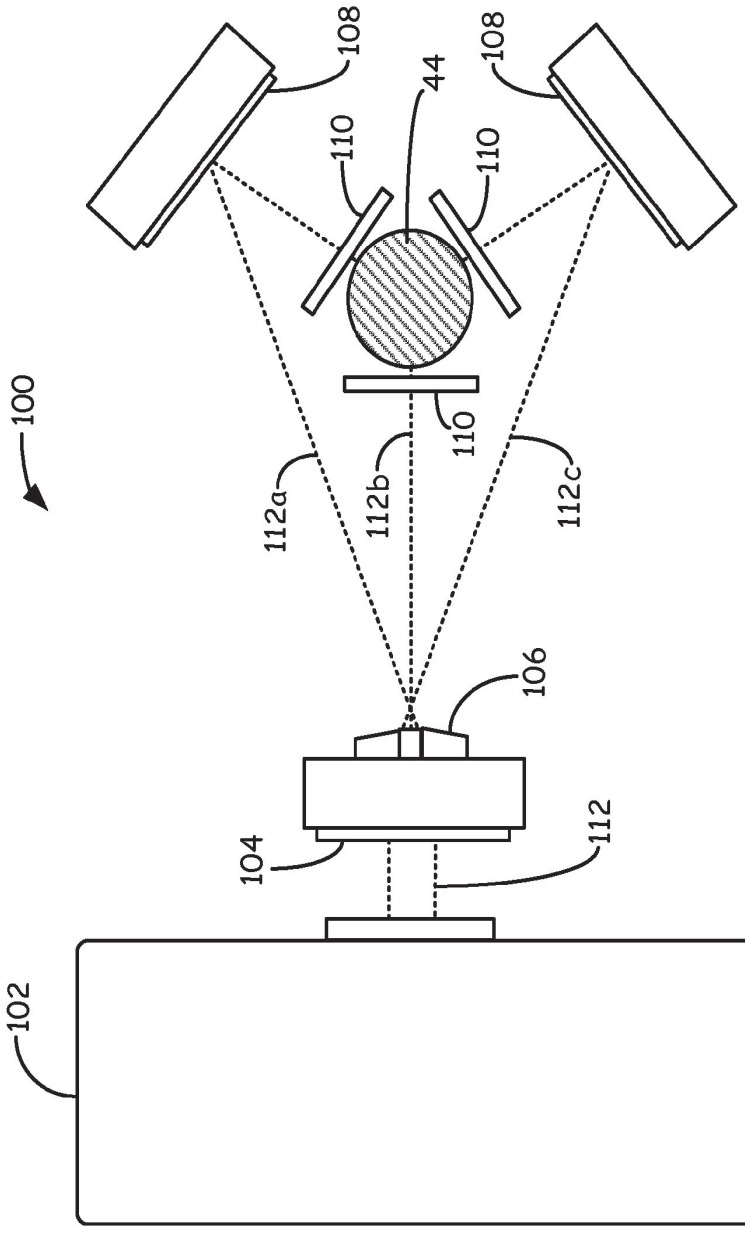


FIG. 6

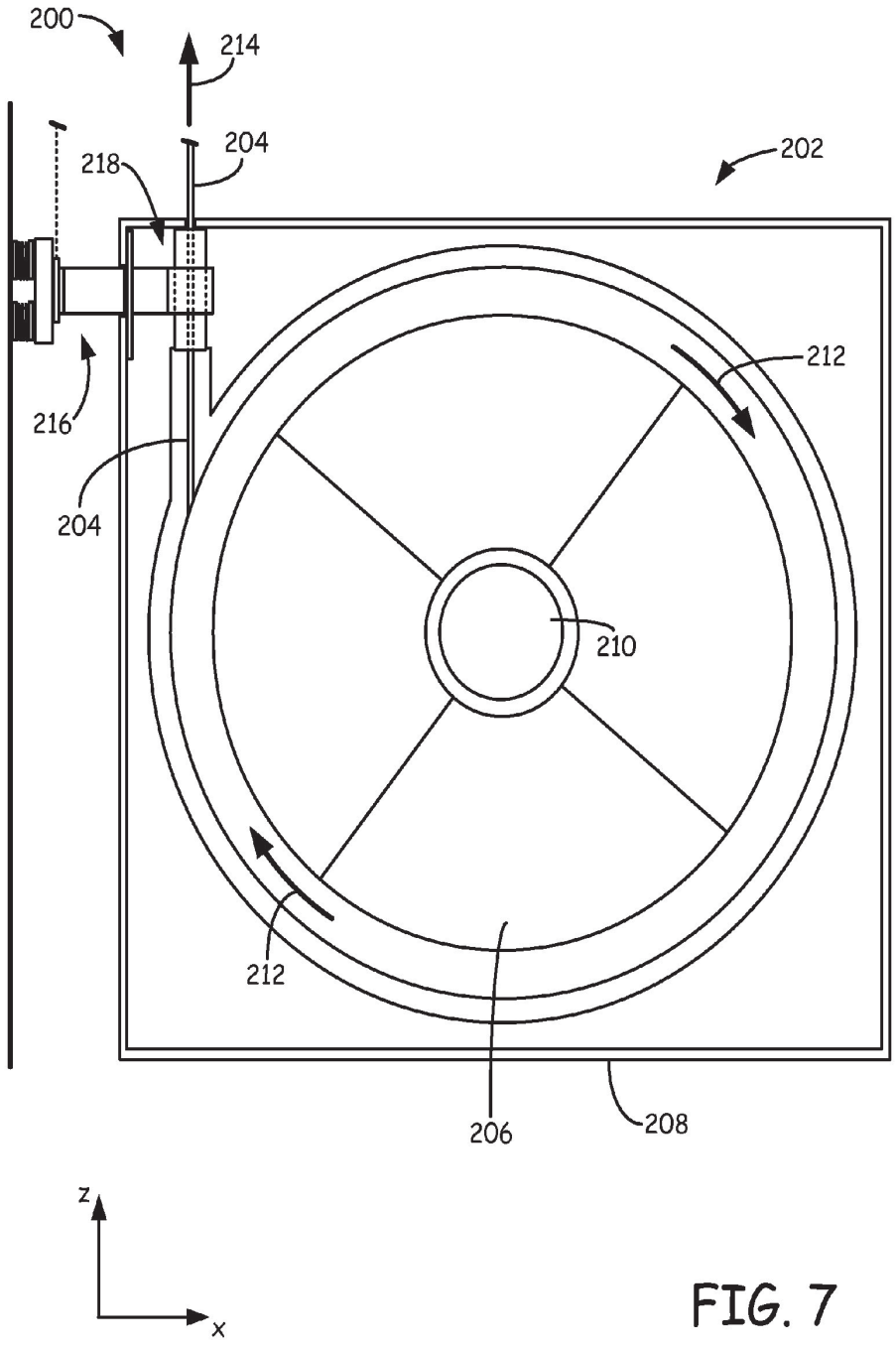


FIG. 7

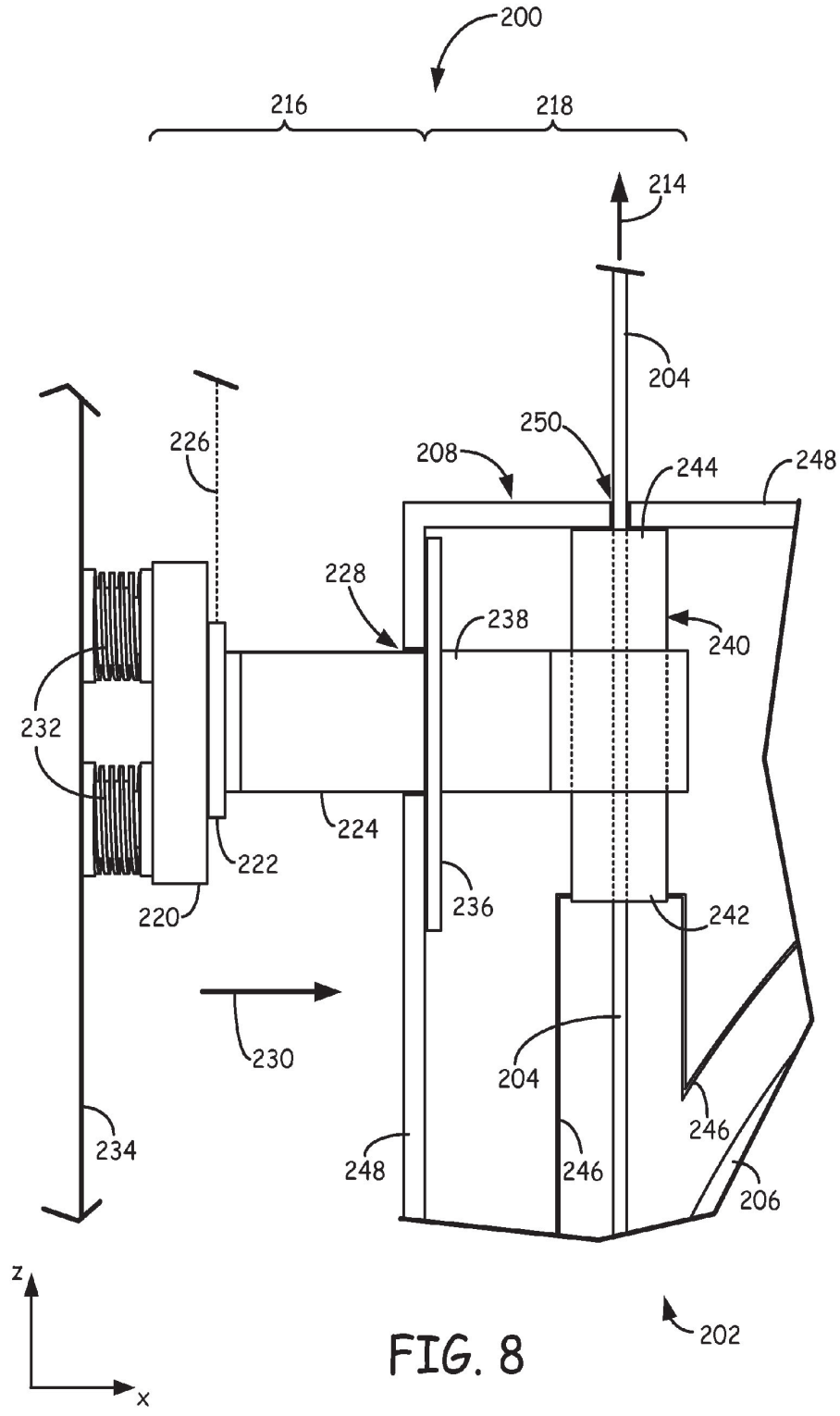

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FIG. 8

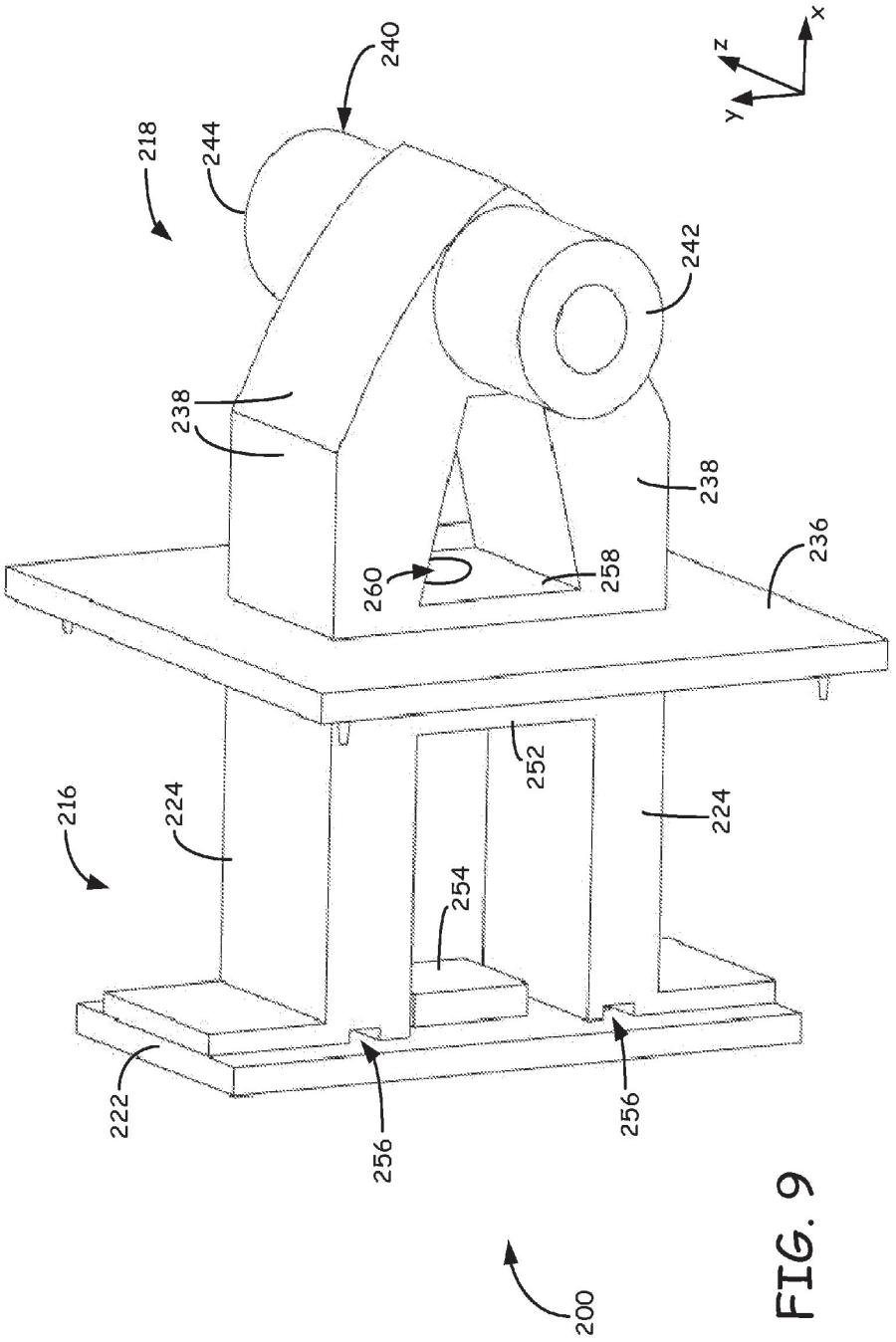

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FIG. 9

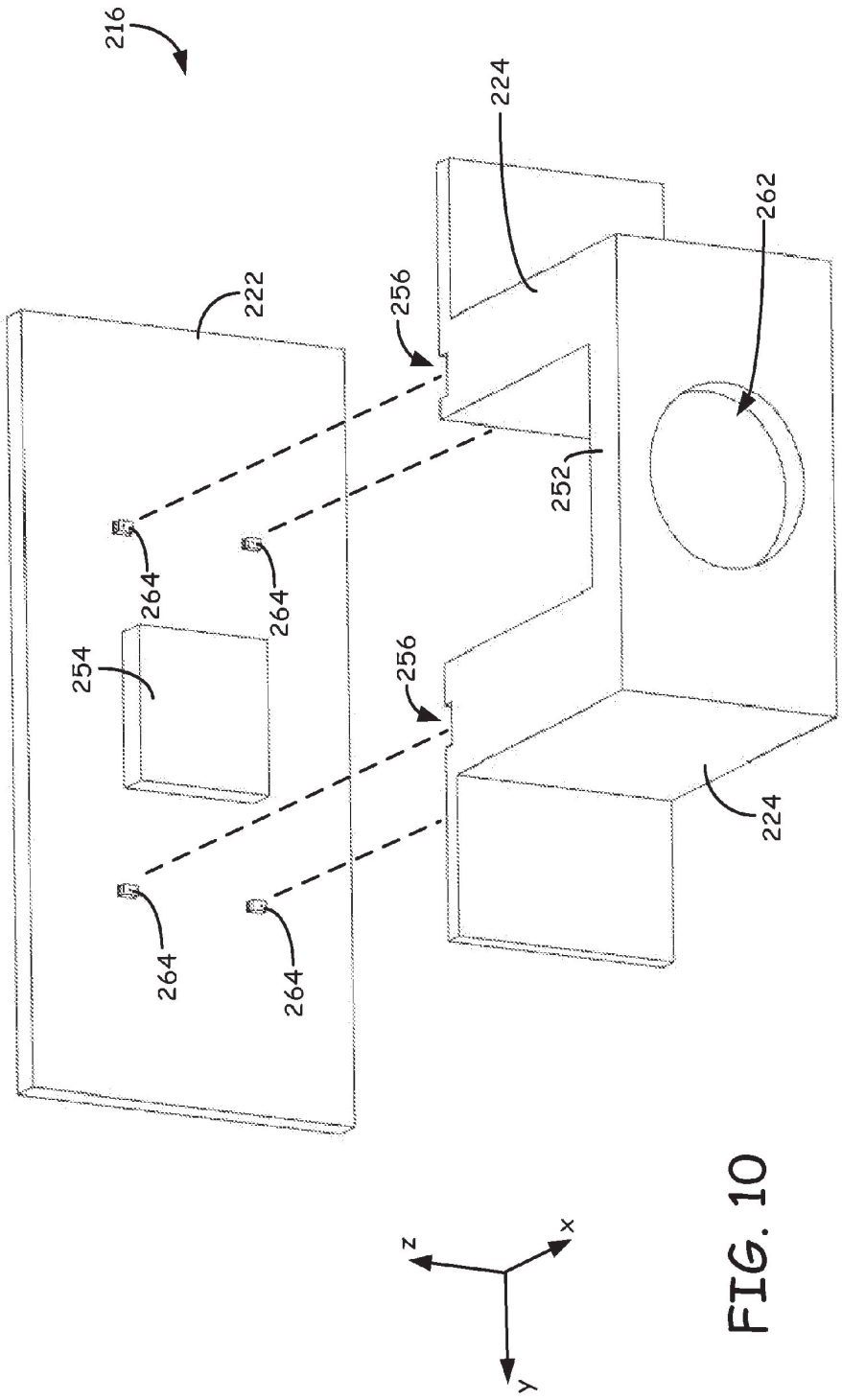


FIG. 10

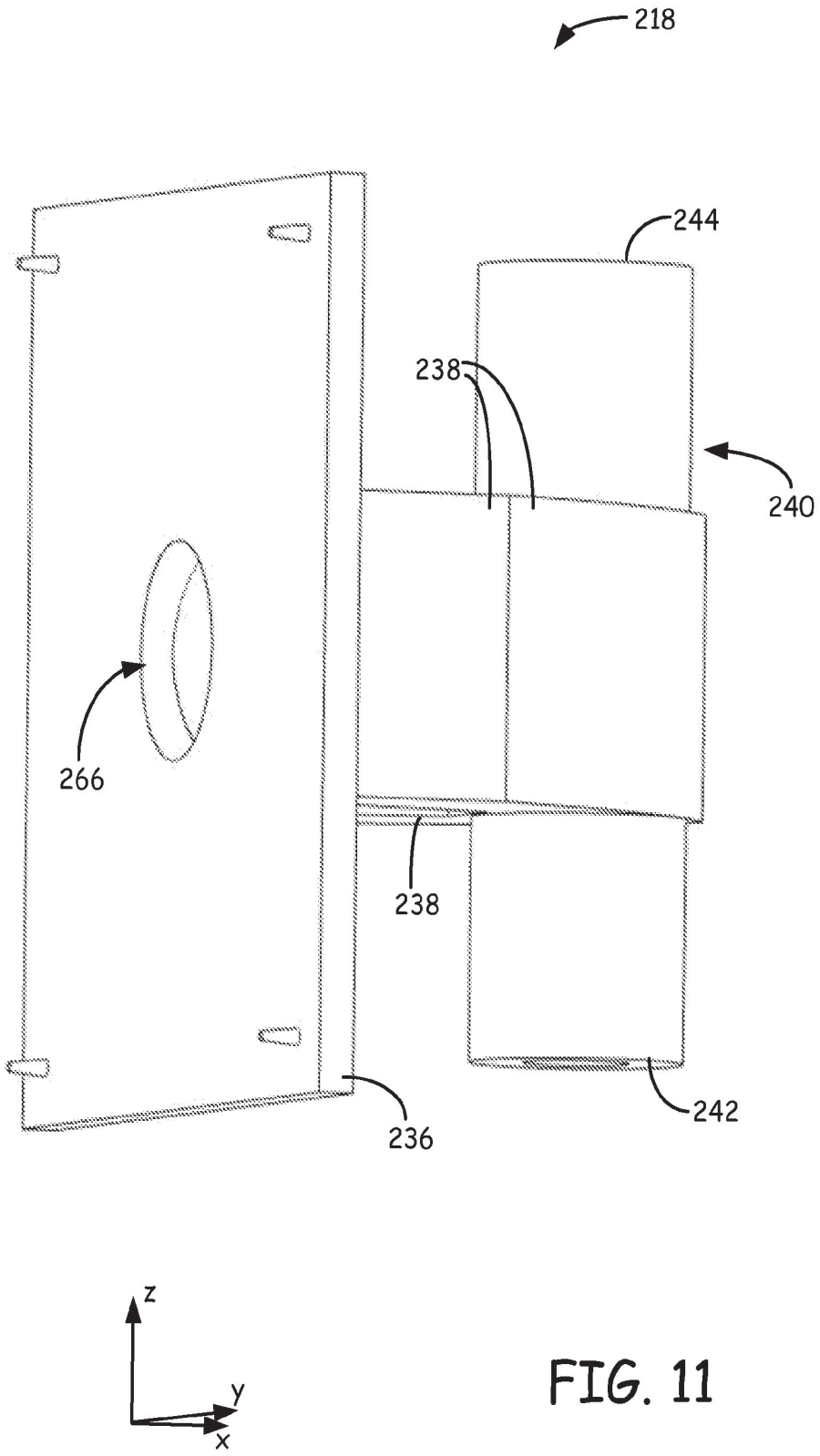


FIG. 11

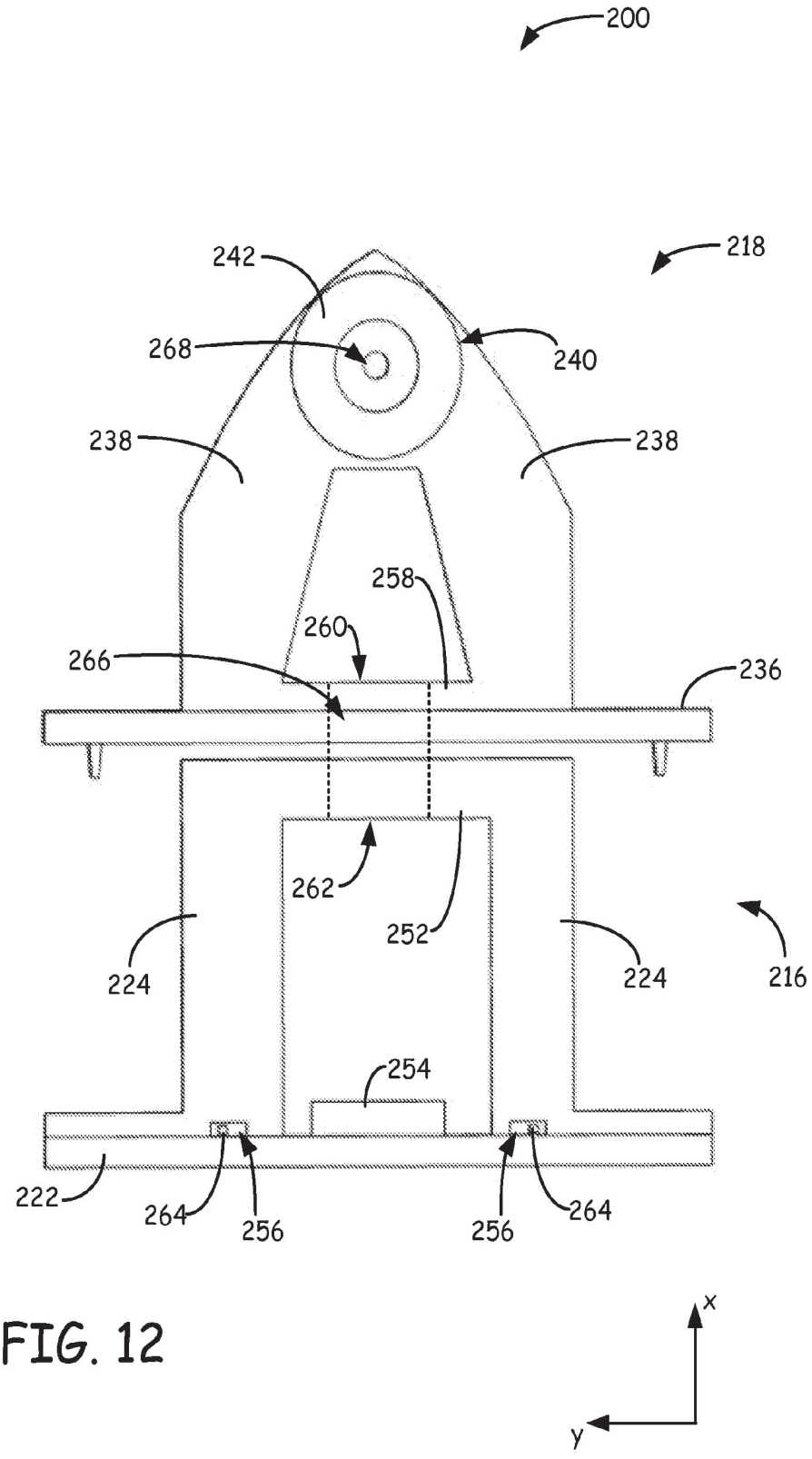

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FIG. 12

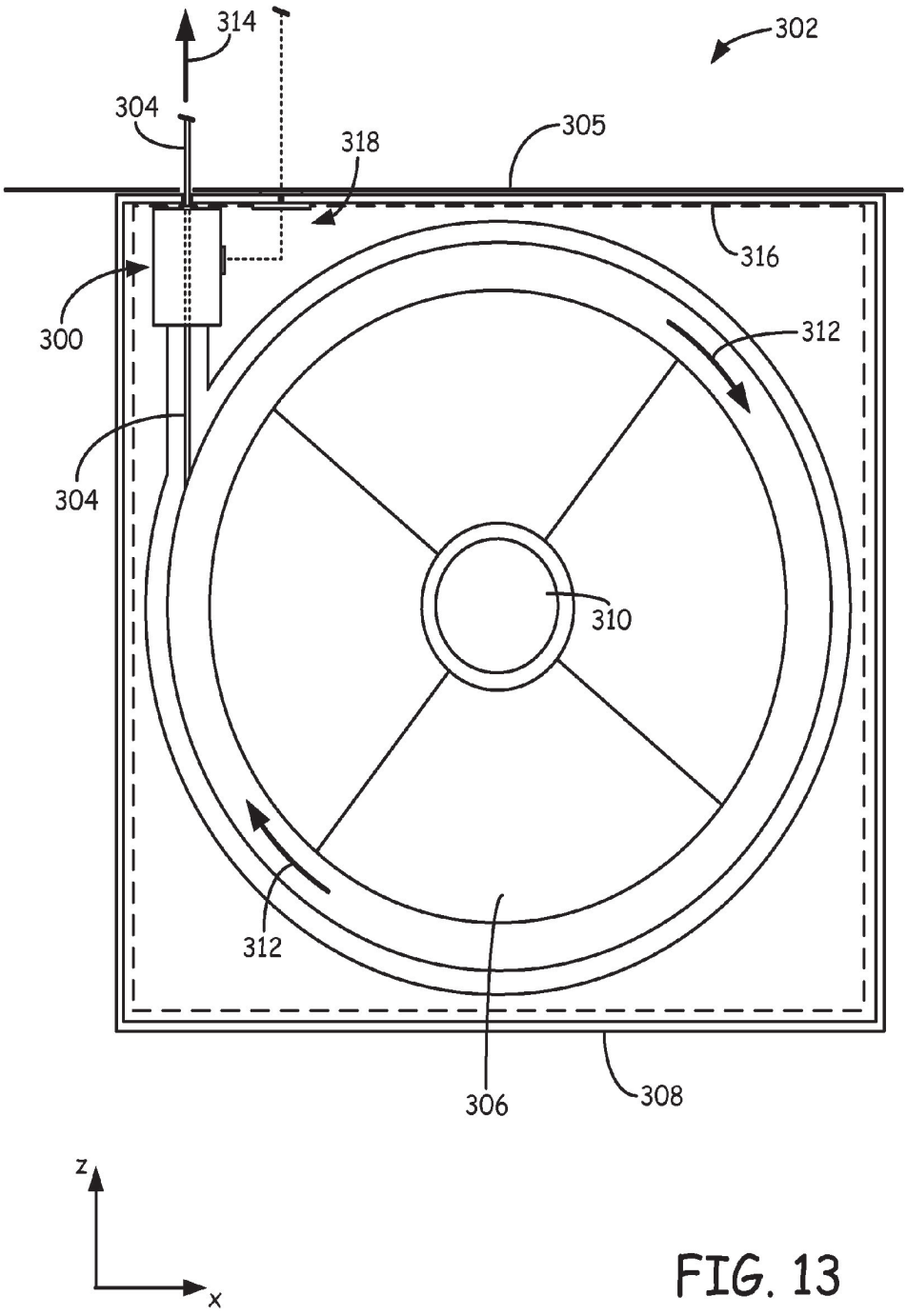


FIG. 13

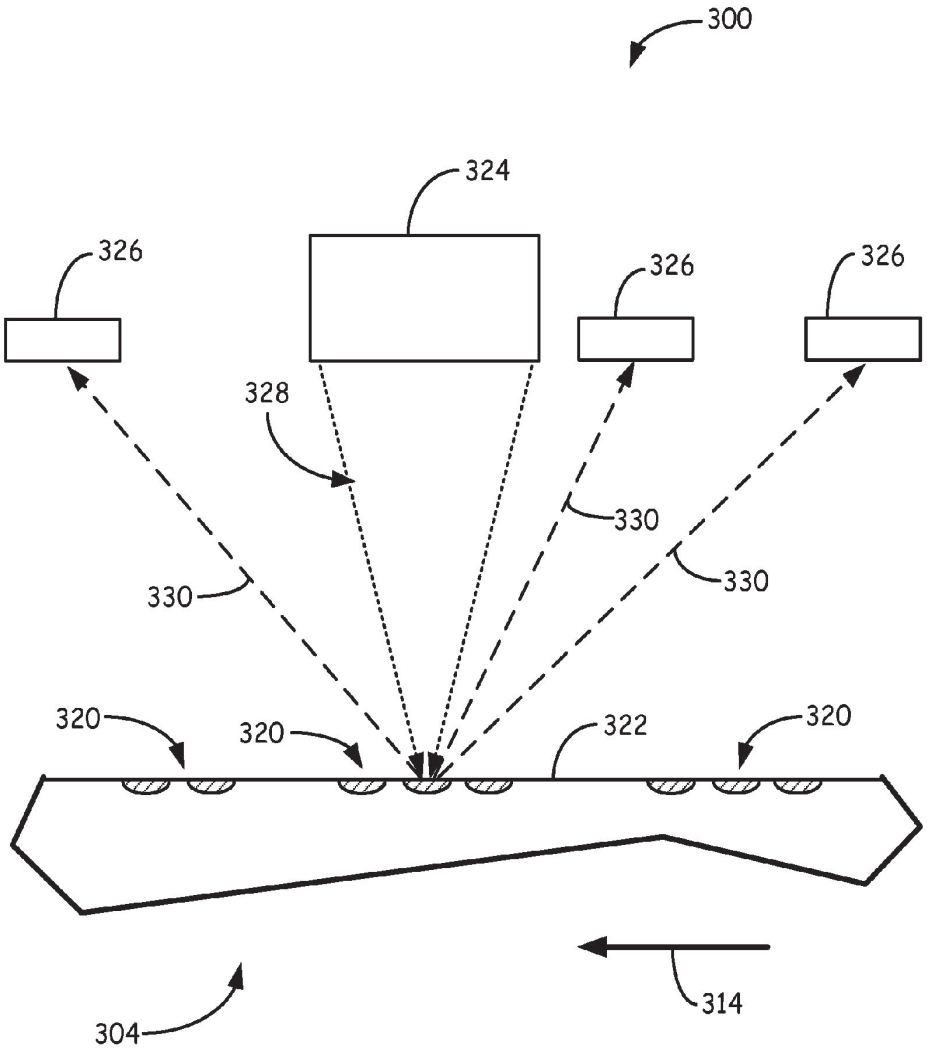


FIG. 14

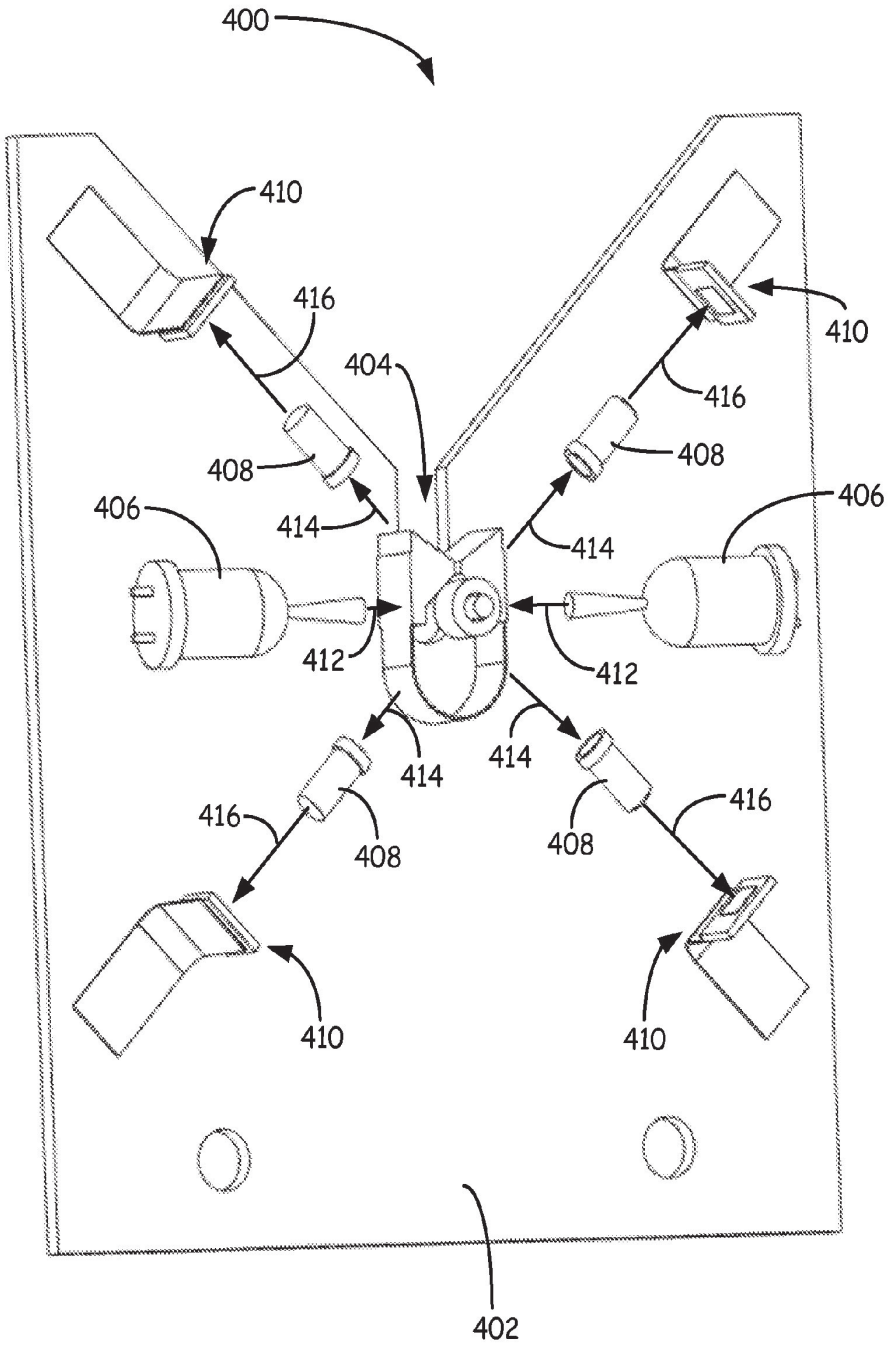

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FIG. 15

ENCODED CONSUMABLE MATERIALS AND SENSOR ASSEMBLIES FOR USE IN ADDITIVE MANUFACTURING SYSTEMS

[0001] CROSS-REFERENCE TO RELATED APPLICATION(S)

[0002] This application is a divisional of U.S. patent application Ser. No. 13/075,667, filed on Mar. 30, 2011; and entitled "Encoded Consumable Materials And Sensor Assemblies For Use In Additive Manufacturing Systems". U.S. patent application Ser. No. 13/075,667 is a continuation-in-part of U.S. patent application Ser. No. 12/949,898, filed on Nov. 19, 2010; and entitled "Encoded Consumable Materials And Sensor Assemblies For Use In Additive Manufacturing Systems".

[0003] U.S. patent application Ser. No. 12/949,898 is a continuation-in-part of U.S. patent application Ser. No. 12/622,042, filed on Nov. 19, 2009, and entitled "Consumable Materials Having Encoded Markings For Use With Direct Digital Manufacturing Systems"; and of U.S. Provisional Patent Application No. 61/262,771, filed on Nov. 19, 2009, and entitled "Optical Sensor Assembly For Use With Consumable Materials Having Encoded Markings".

BACKGROUND

[0004] The present disclosure relates to direct digital or additive manufacturing systems for building three-dimensional (3D) models. In particular, the present disclosure relates to consumable materials, such as modeling and support materials, for use in additive manufacturing systems, such as extrusion-based additive manufacturing systems, and to sensors for use with the consumable materials.

[0005] An extrusion-based, direct digital or additive manufacturing system (e.g., fused deposition modeling systems developed by Stratasys, Inc., Eden Prairie, Minn.) is used to build a 3D model from a digital representation of the 3D model in a layer-by-layer manner by extruding a flowable consumable modeling material. The modeling material is extruded through an extrusion tip carried by an extrusion head, and is deposited as a sequence of roads on a substrate in an x-y plane. The extruded modeling material fuses to previously deposited modeling material, and solidifies upon a drop in temperature. The position of the extrusion head relative to the substrate is then incremented along a z-axis (perpendicular to the x-y plane), and the process is then repeated to form a 3D model resembling the digital representation.

[0006] Movement of the extrusion head with respect to the substrate is performed under computer control, in accordance with build data that represents the 3D model. The build data is obtained by initially slicing the digital representation of the 3D model into multiple horizontally sliced layers. Then, for each sliced layer, the host computer generates a build path for depositing roads of modeling material to form the 3D model.

[0007] In fabricating 3D models by depositing layers of a modeling material, supporting layers or structures are typically built underneath overhanging portions or in cavities of objects under construction, which are not supported by the modeling material itself. A support structure may be built utilizing the same deposition techniques by which the modeling material is deposited. The host computer generates additional geometry acting as a support structure for the overhanging or free-space segments of the 3D model being formed. Consumable support material is then deposited from a second nozzle pursuant to the generated geometry during the build process. The support material adheres to the modeling material during fabrication, and is removable from the completed 3D model when the build process is complete.

SUMMARY

[0008] An aspect of the present disclosure is directed to a marked consumable material for use in an additive manufacturing system. The marked consumable material includes an exterior surface and encoded markings at the exterior surface, where at least a portion of the encoded markings denote volume increments along the marked consumable material. The encoded markings are configured to be read by at least one optical sensor configured to be operated by the additive manufacturing system. The marked consumable material is also configured to be consumed in the additive manufacturing system to build at least a portion of a three-dimensional model.

[0009] Another aspect of the present disclosure is directed to an additive manufacturing system that includes a bay configured to receive a supply of a marked consumable material. The marked consumable material includes an exterior surface and encoded markings at the exterior surface, where the encoded markings extend along at least a portion of a longitudinal length of the marked filament at locations that denote volume increments of the marked consumable material along the longitudinal length. The additive manufacturing system also includes a deposition head configured to receive and dispense the marked consumable material to build a three-dimensional model using a layer-based, additive technique on a platform. The additive manufacturing system further includes a sensor configured to detect the encoded markings of the marked consumable material as the marked consumable material is fed to the deposition head, and a controller in signal communication with the deposition head and the sensor, where the controller is configured to adjust a dispensing rate of the marked consumable material onto the platform in response to the detected encoded markings by the sensor.

[0010] Another aspect of the present disclosure is directed to a method for building a three-dimensional model with an additive manufacturing system. The method includes loading a spool to the additive manufacturing system, where the spool has a marked consumable material comprising an exterior surface having encoded markings, and where at least a portion of the encoded markings denote volume increments of the marked consumable material along a longitudinal length of the marked consumable material. The method also includes feeding the marked consumable material to a deposition head of the additive manufacturing system, and reading information from the encoded markings of the fed marked consumable material with an optical sensor assembly. The method further includes transmitting the read information to a controller of the additive manufacturing system, and adjusting at least one property of the additive manufacturing system based on the transmitted information.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. **1** is a front view of an extrusion-based additive manufacturing system for building 3D models and support structures from marked consumable materials having encoded markings.

[0012] FIG. **1**A is a front view of an alternative extrusion-based additive manufacturing system for building 3D models and support structures from marked consumable materials

having encoded markings, which includes sensor assemblies retained along consumable material pathways of the system.

[0013] FIG. **2** is a perspective view of a segment of a marked cylindrical filament, which is an example of a marked consumable material for use in the extrusion-based additive manufacturing systems.

[0014] FIG. **2**A is a perspective view of a segment of a first example marked cylindrical filament, which includes encoded markings having sub-markings in a binary encoding scheme.

[0015] FIG. **2**B is a perspective and partially exploded view of a segment of a second example marked cylindrical filament, which includes encoded markings denoting volume increments of the filament.

[0016] FIG. **3** is a perspective view of a segment of a marked non-cylindrical filament, which is an additional example of a marked consumable material for use in the extrusion-based additive manufacturing systems.

[0017] FIG. **4** is a perspective view of a marked slug or wafer, which is an additional example of a marked consumable material for use in the extrusion-based additive manufacturing systems.

[0018] FIG. **5** is a flow diagram of a method for manufacturing marked consumable materials.

[0019] FIG. **6** is a schematic illustration of a laser marking system configured to form encoded markings in consumable materials.

[0020] FIG. **7** is a schematic illustration of a sensor assembly of one embodiment of the present disclosure in use with a spooled container, where the sensor assembly contains a first subassembly located within an extrusion-based additive manufacturing system and a second subassembly located within a spooled container.

[0021] FIG. **8** is an expanded view of the sensor assembly shown in FIG. **7**.

[0022] FIG. **9** is a bottom perspective view of the sensor assembly.

[0023] FIG. **10** is an exploded perspective view of the first subassembly of the sensor assembly.

[0024] FIG. **11** is a perspective view of the second subassembly of the sensor assembly.

[0025] FIG. **12** is a bottom view of the sensor assembly, illustrating an engagement and operation of the first and second subassemblies.

[0026] FIG. **13** is a schematic illustration of a sensor assembly of a second embodiment of the present disclosure in use with a spooled container.

[0027] FIG. **14** is an expanded schematic illustration of an example of the second embodied sensor assembly in use with a marked consumable material, where the shown sensor assembly is configured to detect far-field diffraction patterns.

[0028] FIG. **15** is an perspective view of a sensor assembly of a third embodiment of the present disclosure.

DETAILED DESCRIPTION

[0029] The present disclosure is directed to marked consumable materials for use in additive manufacturing systems (also referred to as direct digital manufacturing systems), such as extrusion-based digital manufacturing systems. The marked consumable materials include encoded markings that may contain a variety of information, such as information relating to properties of the marked consumable materials (e.g., physical and compositional properties) and information relating to parameters for operating the additive manufacturing systems (e.g., extrusion parameters).

[0030] The present disclosure is also directed sensor assemblies configured to read the encoded markings from successive portions of the marked consumable materials as the marked consumable materials are fed to the additive manufacturing systems. As discussed below, the sensor assemblies may transmit the information read from the encoded markings to one or more control components of the additive manufacturing systems. This allows the additive manufacturing systems to use the information in the encoded markings for a variety of different purposes, such as for building 3D models and/or support structures.

[0031] FIG. **1** is a front view of system **10**, which is an additive or direct digital manufacturing system, such as an extrusion-based additive manufacturing system. Suitable extrusion-based additive manufacturing systems for system **10** include fused deposition modeling systems developed by Stratasys, Inc., Eden Prairie, Minn. As shown, system **10** includes build chamber **12**, platen **14**, gantry **16**, extrusion head **18**, supply sources **20** and **22**, and sensor assemblies **24** and **26**, where sensor assemblies **24** and **26** are configured to read information from marked consumable materials (not shown in FIG. **1**) provided in supply sources **20** and **22**.

[0032] Build chamber **12** is an enclosed environment that contains platen **14**, gantry **16**, and extrusion head **18** for building a 3D model (referred to as 3D model **28**) and a corresponding support structure (referred to as support structure **30**). Build chamber **12** is desirably heated to reduce the rate at which the modeling and support materials solidify after being extruded and deposited.

[0033] Platen **14** is a platform on which 3D model **28** and support structure **30** are built, and moves along a vertical z-axis based on signals provided from a computer-operated controller (referred to as controller **32**). As shown, controller **32** may communicate with build chamber **12**, platen **14**, gantry **16**, and extrusion head **18** over communication line **33**. While illustrated as a single signal line, communication line **33** may include one or more signal lines for allowing controller **33** to communicate with various components of system **10**, such as build chamber **12**, platen **14**, gantry **16**, and extrusion head **18**.

[0034] Gantry **16** is a guide rail system configured to move extrusion head **18** in a horizontal x-y plane within build chamber **12** based on signals provided from controller **32** (via communication line **33**). The horizontal x-y plane is a plane defined by an x-axis and a y-axis (not shown in FIG. **1**), where the x-axis, the y-axis, and the z-axis are orthogonal to each other. In an alternative embodiment, platen **14** may be configured to move in the horizontal x-y plane within build chamber **12**, and extrusion head **18** may be configured to move along the z-axis. Other similar arrangements may also be used such that one or both of platen **14** and extrusion head **18** are moveable relative to each other.

[0035] Extrusion head **18** is supported by gantry **16** for building 3D model **28** and support structure **30** on platen **14** in a layer-by-layer manner, based on signals provided from controller **32**. Extrusion head **18** includes a pair of drive mechanisms **34***a* and **34***b*, and pair of liquefiers **35***a* and **35***b* configured to receive and melt successive portions of the marked consumable materials. Examples of suitable extrusion heads for extrusion head **18** include those disclosed in LaBossiere, et al., U.S. Patent Application Publication Nos. 2007/0003656 and 2007/00228590; Leavitt, U.S. Patent Applica-

tion Publication No. 2009/0035405; and Batchelder et al., U.S. Pat. Nos. 8,439,665; 8,221,669; and 8,236,227. Alternatively, system **10** may include one or more two-stage pump assemblies, such as those disclosed in Batchelder et al., U.S. Pat. No. 5,764,521; and Skubic et al., U.S. Patent Application Publication No. 2008/0213419. Furthermore, system **10** may include a plurality of extrusion heads **18** for depositing modeling and/or support materials.

[0036] Supply sources **20** and **22** are devices configured to retain supplies of the marked consumable materials, and may be respectively loaded into bays **20***a* and **22***a* of system **10**. In the shown embodiment, supply source **20** retains a supply of a marked modeling material and supply source **22** retains a supply of a marked support material. System **10** may also include additional drive mechanisms (not shown) configured to assist in feeding the marked consumable materials from supply sources **20** and **22** to extrusion head **18**.

[0037] In some embodiments, the marked consumable materials may be provided to system **10** as filaments having marked exterior surfaces (not shown in FIG. **1**), such as marked cylindrical filaments and/or marked non-cylindrical filaments, as discussed below. In these embodiments, suitable assemblies (e.g., spooled containers) for supply sources **20** and **22** include those disclosed in Swanson et al., U.S. Pat. No. 6,923,634; Comb et al., U.S. Pat. No. 7,122,246; Taatjes et al, U.S. Patent Application Publication Nos. 2010/0096485 and 2010/0096489; and Swanson, U.S. Pat. No. 8,403,658 and International Publication No. WO2009/088995.

[0038] In alternative embodiments, the marked consumable materials may be provided to system **10** as marked slugs or wafers, as discussed below. In these embodiments, suitable assemblies for supply sources **20** and **22** include those disclosed in Batchelder et al., U.S. Pat. No. 5,764,521.

[0039] Sensor assemblies **24** and **26** are configured to read the encoded markings of the marked consumable materials as the marked consumable materials are fed to extrusion head **18**. Sensor assembly **24** may be retained at any suitable location between (or within) supply source **20** and extrusion head **18**. Similarly, sensor assembly **26** may be retained at any suitable location between (or within) supply source **22** and extrusion head **18**. In the shown example, sensor assemblies **24** and **26** are retained partially or fully within supply sources **20** and **22**, respectively.

[0040] In alternative embodiments, as disclosed in U.S. Patent Publication No. 2011/0117268 and shown in FIG. **1**A, sensor assemblies **24** and **26** may be retained along filament pathways within system **10** adjacent to supply sources **20** and **22**, respectively. In further alternative embodiments, one or both of sensor assemblies **24** and **26** may be retained by gantry **16** with extrusion head **18**, thereby moving sensor assemblies **24** and **26** with extrusion head **18**.

[0041] As shown in FIG. **1**, the marked modeling material may be provided to extrusion head **18** from supply source **20** through pathway **36**, where pathway **36** may include a guide tube (not shown) for guiding the marked modeling material to extrusion head **18**. In the shown embodiment, pathway **36** is downstream from sensor assembly **24**, thereby allowing sensor assembly **24** to read the encoded information from the marked modeling material prior to passing through pathway **36**. As further shown, sensor assembly **24** may communicate with controller **32** and/or any other control component of system **10** (e.g., a host computer system for system **10**, not shown) over communication line **38**. While illustrated as a single signal line, communication line **38** may include one or more signal lines for allowing sensor assembly **24** to communicate with one or more control components of system **10** (e.g., controller **32**).

[0042] Similarly, the marked support material may be provided to extrusion head **18** from supply source **22** through pathway **40**, where pathway **40** may also include a guide tube (not shown) for guiding the marked support material to extrusion head **18**. In the shown embodiment, pathway **40** is downstream from sensor assembly **26**, thereby allowing sensor assembly **26** to read the encoded information from the marked support material prior to passing through pathway **40**. As further shown, sensor assembly **26** may communicate with controller **32** and/or any other control component of system **10** (e.g., the host computer system for system **10**) over communication line **42**. While illustrated as a single signal line, communication line **42** may include one or more signal lines for allowing sensor assembly **26** to communicate with one or more control components of system **10** (e.g., controller **32**).

[0043] During a build operation, the marked consumable materials may be fed to extrusion head **18** through pathways **36** and **40**. Sensor assemblies **24** and **26** may read the encoded markings of the marked consumable materials as successive portions of the marked consumable materials exit supply sources **20** and **22**, and enter pathways **36** and **40**. Information retained in the encoded markings may then be transmitted to controller **32** over communication lines **38** and **42**, thereby allowing controller **32** to use the received information to assist in building 3D model **28** and/or support structure **30**. For example, controller **32** may modify the extrusion parameters transmitted to extrusion head **18**, allowing the thermal properties and/or the feed rates of extrusion head **18** to be adjusted based on the received information. In one embodiment, the thermal properties and/or the feed rates of extrusion head **18** may be adjusted based on received information relating to the cross sectional areas and/or the volumes of successive portions of the consumable materials.

[0044] Additionally, the received information may relate to the amount of the marked consumable materials remaining in supply source **20** or **22**. This is beneficial for informing a user of system **10** how long the current supply of the marked consumable material will last before the user needs to load a new supply source to system **10**. This information is particularly suitable for allowing the user to know if the build operation will end during a time period when the user may not necessarily be present to load a new supply source to system **10** (e.g., during overnight and/or weekend periods).

[0045] Furthermore, the received information may relate to the marked consumable material itself, such as the material type (e.g., modeling and support materials), material composition, and/or the material color. Sensor assemblies **24** and **26** may read these types of information from the marked consumable materials to confirm that the proper material was loaded to system **10**, thereby reducing the risk of accidentally running system **10** with an incorrect material. For example, sensor assembly **24** may read information from the marked consumable material being fed from supply source **20**, and controller **32** may confirm that the material being fed through pathway **36** is an intended modeling material, rather than a support material.

[0046] Combinations of the read information may also be used to assist in building 3D model **28** and/or support structure **30**. For example, in embodiments in which bays **20***a* and **22***a* may each accept supply sources of modeling and support materials, the user may load supply source **20** of the marked

modeling material into either bay **20***a* or bay **22***a*, and after the corresponding sensor assembly **24** or **26** reads the information from the marked consumable material, controller **32** may identify that the material is a modeling material for building 3D model **28** and adjust the extrusion parameters and feed rates accordingly. A similar arrangement may be accomplished with the marked support material in supply source **22**. This prevents the user from having to load a particular supply source into a particular bay of system **10**.

[0047] As the marked consumable materials are fed to extrusion head **18**, gantry **16** may move extrusion head **18** around in the horizontal x-y plane within build chamber **12**. Extrusion head **18** thermally melts the successive portions of the received marked modeling material, thereby allowing the molten modeling material to be extruded to build 3D model **28**. Similarly, extrusion head **18** thermally melts the successive portions of the marked support material, thereby allowing the molten support material to be extruded to build support structure **30**. The upstream, unmelted portions of the marked consumable materials may each function as a piston with a viscosity-pump action to extrude the molten material out of the respective liquefiers of extrusion head **18**.

[0048] The extruded modeling and support materials are deposited onto platen **14** to build 3D model **28** and support structure **30** using a layer-based additive technique. Support structure **30** is desirably deposited to provide vertical support along the z-axis for overhanging regions of the layers of 3D model **28**. After the build operation is complete, the resulting 3D model **28**/support structure **30** may be removed from build chamber **12**, and support structure **30** may be removed from 3D model **28**. As used herein, the term "three-dimensional model" is intended to encompass any object built with an additive manufacturing system, and includes 3D models built from modeling materials (e.g., 3D model **28**) as well a support structures built from support materials (e.g., support structure **30**).

[0049] FIG. **2** illustrates a segment of filament **44**, which is an example of a suitable marked consumable material of the present disclosure for use as a marked modeling material and/or a marked support material with system **10** (shown in FIG. **1**). As shown in FIG. **2**, filament **44** is a marked cylindrical filament having length **46**, where length **46** is a continuous length that may vary depending on the amount of filament **44** remaining in supply source **20** or **22**. While only a segment of filament **44** is illustrated in FIG. **2**, it is understood that length **46** of filament **44** may extend for a substantial distance (e.g., greater than 25 meters).

[0050] Filament **44** also includes exterior surface **48** extending along length **46** and encoded markings **50**, where encoded markings **50** are located at exterior surface **48** along at least a portion of length **46**. In one embodiment, encoded markings **50** extend substantially along the entire length **46**. Filament **44** also has a surface diameter (referred to as surface diameter **52**) at a non-marked location that is desirably configured to allow filament **44** to mate with a liquefier of extrusion head **18** without undue friction. Examples of suitable average diameters for surface diameter **52** range from about 0.8 millimeters (about 0.03 inches) to about 2.5 millimeters (about 0.10 inches), with particularly suitable average diameters ranging from about 1.0 millimeter (about 0.04 inches) to about 2.3 millimeters (about 0.09 inches), and with even more particularly suitable average diameters ranging from about 1.3 millimeters (about 0.05 inches) to about 2.0 millimeters (about 0.08 inches).

[0051] In the shown embodiment, encoded markings **50** are trench-based markings in exterior surface **48** (e.g., via laser ablation). However, as discussed below, encoded markings **50** may alternatively be form on filament **44** using a variety of different marking techniques. For example, encoded markings **50** may be formed as coatings over exterior surface **48** via one or more coating processes (e.g., jetting and evaporation processes). Alternatively, encoded markings **50** may be formed by cross-linking the surface material of filament **44**, such as with ultraviolet light, to vary the index of refraction of the material at encoded markings **50**. Moreover, encoded markings **50** may be formed by jetting materials that are not readily visible to the naked eye but may be detected using a non-visible wavelength (e.g., ultraviolet-activated materials (e.g., fluorescent materials)). These are particularly suitable in embodiments in which encoded markings **50** function as diffraction gratings. Furthermore, the use of materials that are not readily visible to the naked eye is beneficial for reducing the impact of the encoded markings on the colors of the modeling and support materials.

[0052] Encoded markings **50** include encoded information, which may be read by sensor assembly **24** or **26** as successive portions of filament **44** pass through pathway **36** or **40** of system **10**. As discussed above, the read information may then be transmitted to controller **32** over communication line **38** or **42**, thereby allowing controller **32** to use the received information to assist in building 3D model **28** and/or support structure **30**.

[0053] Encoded markings **50** may extend in multiple linear paths along length **46** (referred to as paths **50***a* and **50***b*), as shown. In this embodiment, encoded markings **50** may also include a third linear path (referred to as path **50***c*, not shown) such that paths **50***a*, **50***b*, and **50***c* are each separated by angles of about 120 degrees. This arrangement is beneficial for allowing sensor assembly **24** or **26** to read at least one of paths **50***a*, **50***b*, and **50***c* regardless of the axial orientation of filament **44** as successive portions of filament **44** pass through the given sensor assembly **24** or **26**. In alternative embodiments, filament **44** may include fewer or additional paths of encoded markings **50** such that filament **44** includes at least one path of encoded markings **50** (e.g., paths **50***a*, **50***b*, and **50***c*). In additional alternative embodiments, one or more of the paths (e.g., paths **50***a*, **50***b*, and **50***c*) may extend along length **46** in a non-linear manner (e.g., S-curves and spiral arrangements).

[0054] Encoded markings **50** may include a variety of different information, such as information relating to filament **44** and/or system **10**. Examples of suitable types of information that may be included in encoded markings **50** include local filament cross-sections (e.g., diameters and root-mean-square variations), volume increments, local and global filament extrusion parameters, length of filament **44** remaining in supply source **20** or **22**, measurements of local filament fingerprint characteristics, material type (e.g., modeling and support materials), material composition, material color, manufacturing information for filament **44** (e.g., manufacturing dates, manufacturing locations, and lot numbers), product codes, material origin information, software and firmware updates for system **10**, and combinations thereof.

[0055] In addition, encoded markings **50** may also include media-based information, such as operating and use instructions, artistic works (e.g., textual, video, and audio information), and the like. In these embodiments, system **10** may include capabilities for playing the encoded media, such as textual and/or graphical information that may be displayed

for a user of system **10** to read, and/or audio information that may be played for a user of system **10** to hear. The amount of data per unit length along length **46** of filament **44** may vary depending on the particular marking technique used, the encoding scheme used, the dimensions of encoded markings **50**, the number of encoded markings per unit length along length **46**, the use of sub-markings (e.g., binary bits), and the like.

[0056] The dimensions and geometries of each mark of encoded markings **50** may vary depending on the encoding scheme and the marking technique used. In the current example in which encoded markings **50** are formed as trenches in exterior surface **48** (e.g., via laser ablation), encoded markings **50** desirably have small dimensions relative to the overall dimensions of filament **44** to minimize or otherwise reduce their impact on the diameter of filament **44**. Additionally, as shown in the current embodiment, the trenches of encoded markings **50** have axial lengths (e.g., axial length **54**) that vary to provide patterns based on the encoding scheme used. In alternative embodiments one or more of the radial widths of the marks (referred to as widths **56**) and/or the depths of the marks may additionally or alternatively be varied to provide patterns based on the encoding scheme used.

[0057] Suitable average dimensions for width **56** range from about 51 micrometers (about 2 mils) to about 510 micrometers (about 20 mils), with particularly suitable average dimensions ranging from about 130 micrometers (about 5 mils) to about 250 micrometers (about 10 mils). Suitable dimensions for the axial lengths along length **46** (e.g., axial length **54**) range from about 130 micrometers (about 5 mils) to about 5,100 micrometers (about 200 mils), with particularly suitable axial lengths ranging from about 1,300 micrometers (about 50 mils) to about 3,800 micrometers (about 150 mils).

[0058] Furthermore, suitable average depths of each mark of encoded markings **50** from exterior surface **48** range from about 1.3 micrometers (about 0.05 mils) to about 51 micrometers (about 2 mils), with particularly suitable average depths ranging from about 13 micrometers (about 0.5 mil) to about 38 micrometers (about 1.5 mils). As discussed below, the edges of the trench marks are suitable regions for scattering light in a darkfield illumination, which may allow an optical sensor assembly to read encoded markings **50** based on the patterns of the scattered light. In alternative embodiments, the encoded markings of filament **44** may be two-dimensional markings (e.g., coatings) rather than the three-dimensional geometry of encoded markings **50**.

[0059] In further alternative embodiments, the axial lengths (e.g., axial length **54**) and the radial widths (e.g., widths **56**) of encoded markings **50** may be the same or substantially the same. In these embodiments, the patterns of encoded markings **50** along length **46** of filament **44** may vary to provide the encoding properties. For example, in embodiments in which encoded markings **50** function as diffraction gratings, encoded markings **50** may be formed as patterns of parallel lines having different indices of refraction from that of exterior surface **48**. The parallel lines of encoded markings **50** may be the same or similar in geometry. However, the patterns of the parallel lines and the interstitial areas of exterior surface **48** may define the encoded pattern in filament **44**.

[0060] Furthermore, each marking of encoded markings **50** may include one or more sub-marks, such as dot patterns suitable for encoding schemes. For example, as shown in FIG. **2**A, each marking of encoded markings **50** may include a single dot corresponding to a "0" and two dots corresponding to a "1", or vice versa, representing a binary encoding scheme. As such, in this embodiment, each marking of encoded markings **50** may retain at least a portion of the encoded information, allowing multiple types of information to be encoded in encoded markings **50**.

[0061] For example, in the shown binary-bit embodiment, the first dot of a dot pair may relate to a first type of encoded information (e.g., volume increments) and the binary pattern of single dots and dot pairs along length **46** may relate to a second type of encoded information. While the dot pairs are illustrated in FIG. **2**A as extending along length **46**, in an alternative embodiment, the dot pairs may extend in the radial direction.

[0062] Filament **44** referred to in FIGS. **2** and **2**A may be manufactured from a variety of extrudable modeling and support materials for respectively building 3D model **28** and support structure **30**. Suitable modeling materials for filament **44** include polymeric and metallic materials. In some embodiments, suitable modeling materials include materials having amorphous properties, such as thermoplastic materials, amorphous metallic materials, and combinations thereof. Examples of suitable thermoplastic materials for filament **44** include acrylonitrile-butadiene-styrene (ABS) copolymers, polycarbonates, polysulfones, polyethersulfones, polyphenylsulfones, polyetherimides, amorphous polyamides, modified variations thereof (e.g., ABS-M30 copolymers), polystyrene, and blends thereof. Examples of suitable amorphous metallic materials include those disclosed in Batchelder, U.S. Patent Application Publication No. 2009/0263582.

[0063] Suitable support materials for filament **44** include polymeric materials. In some embodiments, suitable support materials include materials having amorphous properties (e.g., thermoplastic materials) and that are desirably removable from the corresponding modeling materials after 3D model **28** and support structure **30** are built. Examples of suitable support materials for filament **44** include water-soluble support materials commercially available under the trade designations "SR10", "SR20", and "SR30" Soluble Supports from Stratasys, Inc., Eden Prairie, Minn.; break-away support materials commercially available under the trade designation "BASS" from Stratasys, Inc., Eden Prairie, Minn., and those disclosed in Crump et al., U.S. Pat. No. 5,503,785; Lombardi et al., U.S. Pat. Nos. 6,070,107 and 6,228,923; Priedeman et al., U.S. Pat. No. 6,790,403; and Hopkins et al., U.S. Patent Application Publication No. 2010/0096072.

[0064] The composition of filament **44** may also include additional additives, such as plasticizers, rheology modifiers, inert fillers, colorants, stabilizers, and combinations thereof. Examples of suitable additional plasticizers for use in the support material include dialkyl phthalates, cycloalkyl phthalates, benzyl and aryl phthalates, alkoxy phthalates, alkyl/aryl phosphates, polyglycol esters, adipate esters, citrate esters, esters of glycerin, and combinations thereof. Examples of suitable inert fillers include calcium carbonate, magnesium carbonate, glass spheres, graphite, carbon black, carbon fiber, glass fiber, talc, wollastonite, mica, alumina, silica, kaolin, silicon carbide, composite materials (e.g., spherical and filamentary composite materials), and combinations thereof. In embodiments in which the composition includes additional additives, examples of suitable combined concentrations of the additional additives in the composition range from about

1% by weight to about 10% by weight, with particularly suitable concentrations ranging from about 1% by weight to about 5% by weight, based on the entire weight of the composition.

[0065] Filament **44** also desirably exhibits physical properties that allow filament **44** to be used as a consumable material in system **10**. For example, filament **44** is desirably flexible along length **46** to allow filament **44** to be retained in supply sources **20** and **22** (e.g., wound on spools) and to be fed through system **10** (e.g., through pathways **36** and **40**) without plastically deforming or fracturing. For example, in one embodiment, filament **44** is capable of withstanding elastic strains greater than t/r, where "t" is a cross-sectional thickness of filament **44** in the plane of curvature, and "r" is a bend radius (e.g., a bend radius in supply source **20** or **22** and/or a bend radius through pathway **36** or **40**).

[0066] In one embodiment, the composition of filament **44** is substantially homogenous along length **46**. Additionally, the composition of filament **44** desirably exhibits a glass transition temperature that is suitable for use in build chamber **12**. Examples of suitable glass transition temperatures at atmospheric pressure for the composition of filament **44** include temperatures of about 80° C. or greater. In some embodiments, suitable glass transition temperatures include about 100° C. or greater. In additional embodiments, suitable glass transition temperatures include about 120° C. or greater.

[0067] Filament **44** also desirably exhibits low compressibility such that its axial compression doesn't cause filament **44** to be seized within a liquefier. Examples of suitable Young's modulus values for the polymeric compositions of filament **44** include modulus values of about 0.2 gigapascals (GPa) (about 30,000 pounds-per-square inch (psi)) or greater, where the Young's modulus values are measured pursuant to ASTM D638-08. In some embodiments, suitable Young's modulus range from about 1.0 GPa (about 145,000 psi) to about 5.0 GPa (about 725,000 psi). In additional embodiments, suitable Young's modulus values range from about 1.5 GPa (about 200,000 psi) to about 3.0 GPa (about 440,000 psi).

[0068] FIG. **2**B illustrates an example embodiment of filament **44**, in which encoded markings **50** designate volume increments of filament **44** along length **46**. This is in comparison to length increments of filament **44** along length **46**, which do not account for variations in the diameter or cross-sectional area of filament **44**. As shown, each marking of encoded markings **50** may be offset along length **46** from a successive marking by distance denoting a volume increment (e.g., every 500 cubic micro-inches).

[0069] The volume of a given segment of filament **44** is the product of the cross-sectional area of filament **44** for the segment and the length of the segment along length **46**. As such, in embodiments in which surface diameter **52** is constant along length **46**, the distances between each marking of encoded markings **50** may be the same or substantially the same to maintain the same volume increment between each marking. However, in embodiments in which surface diameter **52** may vary along length **46** (e.g., fluctuations around a target diameter), the distances between each marking of encoded markings **50** may differ to maintain the same volume increment between each marking.

[0070] For example, as shown in FIG. **2**B, encoded markings **50** extend along length **46**, and include example markings $\mathbf{50}_i$, $\mathbf{50}_{i+1}$, and $\mathbf{50}_{i+2}$. Marking $\mathbf{50}_{i+1}$ is offset along length **46** from marking **50**, by distance **57***a* to define filament segment **44***a*, and marking $\mathbf{50}_{i+2}$ is offset along length **46** from marking $\mathbf{50}_{i+1}$ by distance **57***b* to define filament segment **44***b*. Filament segments **44***a* and **44***b* desirably have the same or substantially the same volumes, based on a predetermined volume increment. As such, if the average surface diameter **52** of filament segment **44***a* (referred to as surface diameter **52***a*) is the same as the average surface diameter **52** of filament segment **44***b* (referred to as surface diameter **52***b*), then lengths **57***a* and **57***b* may be the same to maintain the predetermined volume increment.

[0071] However, if surface diameter **52***a* of filament segment **44***a* is different from surface diameter **52***b* of filament segment **44***b*, then lengths **57***a* and **57***b* may differ to maintain the same predetermined volume increment. In particular, if surface diameter **52***a* of filament segment **44***a* is less than surface diameter **52***b* of filament segment **44***b*, then length **57***a* may be greater than length **57***b* by an extent such that the volumes of filament segments **44***a* and **44***b* are the same or substantially the same. Alternatively, if surface diameter **52***a* of filament segment **44***a* is greater than surface diameter **52***b* of filament segment **44***b*, then length **57***a* may be less than length **57***b* by an extent such that the volumes of filament segments **44***a* and **44***b* are the same or substantially the same.

[0072] As mentioned above, during a build operation, information retained in encoded markings **50** may be read by system **10** and transmitted to controller **32**. In the embodiment shown in FIG. **2**B, each marking of encoded markings **50** denotes a volume increment of the consumable material. Alternatively, each marking of encoded markings **50** may include sub-markings (e.g., dots for a binary encoding scheme), such that a portion of each marking of encoded markings **50** may denote the volume increment of the consumable material (and the binary pattern along length **46** may represent a second type of encoded information). With this information, controller **32** may modify the extrusion parameters transmitted to extrusion head **18**, allowing the thermal properties and/or the feed rates of extrusion head **18** to be adjusted based on the received information.

[0073] For example, when sensor assembly **24** reads markings $\mathbf{50}_i$ and $\mathbf{50}_{i+1}$ and transmits the readings to controller **32**, controller **32** may determine the duration between when sensor assembly **24** reads markings $\mathbf{50}_i$ and $\mathbf{50}_{i+1}$, and the feed rate of filament **44** during the determined duration. Based on this information controller **32** may direct drive mechanism **34***a* to adjust the feed rate of filament **44** when filament segment **44***a* reaches drive mechanism **34***a*.

[0074] Similarly, when sensor assembly **24** then reads marking $\mathbf{50}_{i+2}$ and information may be transmitted to controller **32**, and controller **32** may direct drive mechanism **34***a* to further adjust the feed rate of filament **44** when filament segment **44***b* reaches drive mechanism **34***a* (or drive mechanism **34***b*). This process may continue for each successive volume increment of filament **44**, thereby increasing the control over the amounts of the consumable material extruded from extrusion head **18**. Controlling the operation of system **10** based on the read volume increments provides greater control over the extrusion properties of the consumable material, and may compensate for variations in the cross-sectional areas of filament **44** along length **46**. As such, system **10** may extrude precise volumes of the consumable material from liquefier assembly **34***a* (or liquefier assembly **34***b*), resulting in better part quality in 3D model **28** and/or support structure **30**.

[0075] As discussed below, during the manufacture of filament **44** as shown in FIG. **2**A, encoded markings **50** may be marked at exterior surface **48** using a variety of different techniques based on the volume increments. For example, encoded markings **50** may be marked with the use of a phase-lock-loop (PLL) control system, where the phases of the output marking locations along length **46** may be varied based on input diameter or cross-sectional area measurements.

[0076] In this embodiment, after the precursor for filament **44** is formed and solidified, the precursor may travel at a predetermined line speed, and the diameters or cross-sectional areas of the precursor may be measured over successive segments along length **46**. These measured values may then be retained in one or more computer systems. As the precursor travels at the predetermined line speed, encoded markings **50** may then be formed at exterior surface **48** based on the measured diameters or cross-sectional areas. For example, encoded markings **50** may be formed by jetting materials that are not readily visible to the naked eye but may be detected using a non-visible wavelength (e.g., ultraviolet-activated materials). The PLL control system may vary the timing of the marking phase based on the measured diameters or cross-sectional areas to maintain the same or substantially the same volume increments of filament **44** between each successive marking. Furthermore, encoded markings **50** may alternatively include multiple paths (e.g., paths **50***a*, **50***b*, and **50***c*) as discussed above for the embodiment of filament **44** shown in FIGS. **2** and **2**A.

[0077] The resulting filament **44** may then be wound up on a spool for subsequent storage and use in system **10**. The above-discussed process allows filament **44** to be manufactured in a continuous process, where the precursor may be formed, solidified, measured, marked, and spooled in a continuous manner. In alternative embodiments, one or more of these steps may be performed in batch operations. For example, the measurement step may be performed separately from the marking step, where the measurements may be retained in one or more computer systems prior to being used with the PLL control system.

[0078] FIG. **3** illustrates a segment of filament **58**, which is an additional example of a suitable marked consumable material of the present disclosure for use as a modeling material and/or a support material with system **10** (shown in FIG. **1**). As shown in FIG. **3**, filament **58** is a marked non-cylindrical filament having length **60**, where length **60** is a continuous length that may vary depending on the amount of filament **58** remaining in supply source **20** or **22**. While only a segment of filament **58** is illustrated in FIG. **3**, it is understood that length **60** of filament **58** may extend for a substantial distance (e.g., greater than 25 meters).

[0079] Filament **58** also includes exterior surface **62** extending along length **60** and having major surfaces **64** and **66**, which are the opposing major surfaces of filament **58**. Filament **58** further includes encoded markings **68** located at major surface **64** of exterior surface **62**, along at least a portion of length **60**. In one embodiment, encoded markings **68** extend substantially along the entire length **60**.

[0080] In the shown embodiment, encoded markings **68** are trench-based markings in exterior surface **62** (e.g., via laser ablation), as discussed above for encoded markings **50** of filament **44** (shown in FIG. **2**). However, as discussed below, encoded markings **68** may alternatively be formed on filament **58** using a variety of different marking techniques (e.g., via one or more coating processes). For example, encoded markings **68** may be formed by cross-linking the surface material of filament **58**, such as with ultraviolet light, to vary the index of refraction of the material at encoded markings **68**. Moreover, encoded markings **68** may be formed by jetting materials that are not readily visible to the naked eye but may be detected using a non-visible wavelength (e.g., ultraviolet-activated materials). These are particularly suitable in embodiments in which encoded markings **68** function as diffraction gratings and/or as binary bits (with sub-marks).

[0081] Encoded markings **68** may extend in a single linear path along length **60** at major surface **64**, as shown. In comparison to filament **44**, which has a cylindrical cross section, filament **58** is less susceptible to axial rotation due to its rectangular cross section. As such, so long as filament **58** is provided to system **10** in the proper orientation, sensor assembly **24** or **26** may read encoded markings **68** as successive portions of filament **58** pass through the given sensor assembly **24** or **26**. In an alternative embodiment, encoded markings **50** may also include an additional linear path along length **60** at major surface **66**, and/or along the edges of filament **58**. This embodiment allows sensor assembly **24** or **26** to read encoded markings **68** regardless of the orientation of filament **58**. In additional alternative embodiments, filament **58** may include additional paths of encoded markings **68** at one or both of major surfaces **64** and **66**. Furthermore, one or more of the paths of encoded markings **68** may extend along length **60** in a non-linear manner (e.g., S-curves and spiral arrangements).

[0082] Encoded markings **68** may include a variety of different information, such as information relating to filament **58** and/or system **10**, which may be read by sensor assembly **24** or **26** in the same manner as discussed above for encoded markings **50** of filament **44**. Accordingly, suitable types of information that may be retained in encoded markings **68** include those discussed above for encoded markings **50** (e.g., volume increments based on the cross-sectional areas along length **60**).

[0083] Filament **58** has a cross section defined by width **70** and thickness **72**, thereby defining a non-cylindrical cross section. Examples of suitable non-cylindrical filaments for filament **58** include those disclosed in Batchelder et al., U.S. Pat. Nos. 8,439,665; 8,221,669; and 8,236,227. Filament **58** is also desirably flexible along length **60** to allow filament **58** to be retained in supply sources **20** and **22** (e.g., wound on spools) and to be fed through system **10** (e.g., through pathways **36** and **40**) without plastically deforming or fracturing. For example, in one embodiment, filament **58** is capable of withstanding elastic strains greater than t/r, where "t" is a cross-sectional thickness of filament **58** in the plane of curvature, and "r" is a bend radius (e.g., a bend radius in supply source **20** or **22** and/or a bend radius through pathway **36** or **40**).

[0084] Examples of suitable average dimensions for width **70** range from about 1.0 millimeter (about 0.04 inches) to about 10.2 millimeters (about 0.40 inches), with particularly suitable average widths ranging from about 2.5 millimeters (about 0.10 inches) to about 7.6 millimeters (about 0.30 inches), and with even more particularly suitable average widths ranging from about 3.0 millimeters (about 0.12 inches) to about 5.1 millimeters (about 0.20 inches).

[0085] Examples of suitable average dimensions for thickness **72** range from about 0.08 millimeters (about 0.003 inches) to about 1.5 millimeters (about 0.06 inches), with particularly suitable average thicknesses ranging from about

0.38 millimeters (about 0.015 inches) to about 1.3 millimeters (about 0.05 inches), and with even more particularly suitable average thicknesses ranging from about 0.51 millimeters (about 0.02 inches) to about 1.0 millimeter (about 0.04 inches).

[0086] Examples of suitable aspect ratios of width **70** to thickness **72** include aspect ratios greater than about 2:1, with particularly suitable aspect ratios ranging from about 2.5:1 to about 20:1, and with even more particularly suitable aspect ratios ranging from about 3:1 to about 10:1.

[0087] The dimensions and geometries of each mark of encoded markings **68** may also vary depending on the encoding scheme and the marking technique used. In the current example in which encoded markings **68** are formed as trenches in exterior surface **62** (e.g., via laser ablation), encoded markings **68** desirably have small dimensions relative to the overall dimensions of filament **58** to minimize or otherwise reduce their impact on the cross sectional area of filament **58**.

[0088] Additionally, as shown in the current embodiment, the trenches of encoded markings **68** have axial lengths (along length **60**) that vary to provide patterns based on the encoding scheme used. In alternative embodiments one or more of the widths of the marks (along width **70**) and/or the depths of the marks (along thickness **72**) may additionally or alternatively be varied to provide patterns based on the encoding scheme used. Examples of suitable axial lengths, widths, and depths for each mark of encoded markings **68** include those discussed above for encoded markings **50** of filament **44**.

[0089] Furthermore, the axial lengths along length **60** and the widths along widths **70** of encoded markings **68** may be the same or substantially the same. In these embodiments, the patterns of encoded markings **68** along length **60** of filament **58** may vary to provide the encoding properties. For example, in embodiments in which encoded markings **68** function as diffraction gratings, encoded markings **68** may be formed as patterns of parallel lines having different indices of refraction from that of major surface **64** and/or major surface **66**. The parallel lines of encoded markings **68** may be the same or similar in geometry. However, the patterns of the parallel lines and the interstitial areas of major surface **64** and/or major surface **66** may define the encoded pattern in filament **58**.

[0090] Alternatively, each marking of encoded markings **68** may include sub-markings (e.g., dots for a binary encoding scheme). In this embodiment, a portion of each marking of encoded markings **68** may denote a first type of encoded information (e.g., volume increments), and the binary pattern along length **60** may represent a second type of encoded information.

[0091] Filament **58** may also be manufactured from a variety of extrudable modeling and support materials for respectively building 3D model **28** and support structure **30**. Examples of suitable modeling and support materials include those discussed above for filament **44**. Filament **58** also desirably exhibits physical properties that allow filament **58** to be used as a consumable material in system **10**. In one embodiment, the composition of filament **58** is substantially homogenous along length **60**. Additionally, the composition of filament **58** desirably exhibits a glass transition temperature that is suitable for use in build chamber **12**. Examples of suitable glass transition temperatures at atmospheric pressure for the composition of filament **58** include those discussed above for filament **44**. Filament **58** also desirably exhibits low compressibility such that its axial compression doesn't cause filament **58** to be seized within a liquefier. Examples of suitable Young's modulus values for the polymeric compositions of filament **58** include those discussed above for filament **44**.

[0092] FIG. **4** illustrates slug or wafer **74**, which is an additional example of a suitable marked consumable material of the present disclosure for use as a modeling material and/or a support material with system **10** (shown in FIG. **1**). As shown in FIG. **4**, slug **74** dimensionally includes length **76**, width **78**, and thickness **80**. Examples of suitable designs for slug **74** include those disclosed in Batchelder et al., U.S. Pat. No. 5,764,521. Accordingly, a series of slugs **74** may be fed through pathway **36** or **40** in an end-to-end arrangement to provide slugs **74** to extrusion head **18**.

[0093] Slug **74** also includes exterior surface **82** extending along length **76**, and encoded markings **84** located at exterior surface **82**, along at least a portion of length **76**. In one embodiment, encoded markings **84** extend substantially along the entire length **86**. In the shown embodiment, encoded markings **84** are trench-based markings in exterior surface **82** (e.g., via laser ablation), as discussed above for encoded markings **50** of filament **44** (shown in FIG. **2**). However, as discussed below, encoded markings **84** may alternatively be written to slug **74** using a variety of different marking techniques (e.g., via one or more coating processes). For example, encoded markings **84** may be formed by cross-linking the surface material of slug **74**, such as with ultraviolet light, to vary the index of refraction of the material at encoded markings **84**. Moreover, encoded markings **84** may be formed by jetting materials that are not readily visible to the naked eye but may be detected using a non-visible wavelength (e.g., ultraviolet-activated materials). This is particularly suitable in embodiments in which encoded markings **84** function as diffraction gratings and/or as binary bits (with sub-marks).

[0094] Encoded markings **84** may extend in a single linear path along length **76** at one or both major surfaces of exterior surface **82**, as shown. In additional alternative embodiments, slug **74** may include additional paths of encoded markings **84** at one or both of major surfaces of exterior surface **82**. Furthermore, one or more of the paths of encoded markings **84** may extend along length **76** in a non-linear manner (e.g., S-curves and spiral arrangements).

[0095] Encoded markings **84** may also include a variety of different information, such as information relating to slug **74** and/or system **10**, which may be read by sensor assembly **24** or **26** in the same manner as discussed above for encoded markings **50** of filament **44**. Accordingly, suitable types of information that may be retained in encoded markings **84** include those discussed above for encoded markings **50** (e.g., volume increments based on the cross-sectional areas along length **76**).

[0096] Examples of suitable average dimensions for length **76** range from about 25 millimeters (about 1.0 inch) to about 150 millimeters (about 6.0 inches), with particularly suitable average lengths ranging from about 38 millimeters (about 1.5 inches) to about 76 millimeters (about 3.0 inches), and with even more particularly suitable average lengths ranging from about 43 millimeters (about 1.7 inches) to about 64 millimeters (about 2.5 inches).

[0097] Examples of suitable average dimensions for width **78** range from about 10 millimeters (about 0.4 inches) to about 38 millimeters (about 1.5 inches), with particularly suitable average widths ranging from about 13 millimeters

(about 0.5 inches) to about 33 millimeters (about 1.3 inches), and with even more particularly suitable average widths ranging from about 15 millimeters (about 0.6 inches) to about 25 millimeters (about 1.0 inch).

[0098] Examples of suitable average dimensions for thickness **80** range from about 1.3 millimeters (about 0.05 inches) to about 13 millimeters (about 0.5 inches), with particularly suitable average thicknesses ranging from about 2.5 millimeters (about 0.1 inches) to about 7.6 millimeters (about 0.3 inches), and with even more particularly suitable average thicknesses ranging from about 3.8 millimeters (about 0.15 inches) to about 6.4 millimeters (about 0.25 inches).

[0099] The dimensions and geometries of each mark of encoded markings **84** may also vary depending on the encoding scheme and the marking technique used. In the current example in which encoded markings **84** are formed as trenches in exterior surface **82** (e.g., via laser ablation), encoded markings **84** desirably have small dimensions relative to the overall dimensions of slug **74** to minimize or otherwise reduce their impact on the cross sectional area of slug **74**.

[0100] Additionally, as shown in the current embodiment, the trenches of encoded markings **84** have axial lengths (along length **76**) that vary to provide patterns based on the encoding scheme used. In alternative embodiments one or more of the widths of the marks (along width **78**) and/or the depths of the marks (along thickness **80**) may additionally or alternatively be varied to provide patterns based on the encoding scheme used. Examples of suitable axial lengths, widths, and depths for each mark of encoded markings **84** include those discussed above for encoded markings **50** of filament **44**.

[0101] Furthermore, the axial lengths and the widths of encoded markings **84** may be the same or substantially the same. In these embodiments, the patterns of encoded markings **84** along the length of slug **74** may vary to provide the encoding properties. For example, in embodiments in which encoded markings **84** function as diffraction gratings, encoded markings **84** may be formed as patterns of parallel lines having different indices of refraction from that of exterior surface **82**. The parallel lines of encoded markings **84** may be the same or similar in geometry. However, the patterns of the parallel lines and the interstitial areas of exterior surface **82** may define the encoded pattern in slug **74**.

[0102] Alternatively, each marking of encoded markings **84** may include sub-markings (e.g., dots for a binary encoding scheme). In this embodiment, a portion of each marking of encoded markings **84** may denote a first type of encoded information (e.g., volume increments), and the binary pattern along the length of slug **74** may represent a second type of encoded information.

[0103] Slug **74** may also be manufactured from a variety of extrudable modeling and support materials for respectively building 3D model **28** and support structure **30**. Examples of suitable modeling and support materials include those discussed above for filament **44**. Slug **74** also desirably exhibits physical properties that allow slug **74** to be used as a consumable material in system **10**. In one embodiment, the composition of slug **74** is substantially homogenous along length **76**. Additionally, the composition of slug **74** desirably exhibits a glass transition temperature that is suitable for use in build chamber **12**. Examples of suitable glass transition temperatures at atmospheric pressure for the composition of slug **74** include those discussed above for filament **44**. Slug **74** also desirably exhibits low compressibility such that its axial compression doesn't cause slug **74** to be seized within a liquefier. Examples of suitable Young's modulus values for the polymeric compositions of slug **74** include those discussed above for filament **44**.

[0104] In addition to the above-discussed marked consumable material geometries, the marked consumable materials of the present disclosure include a variety of geometries, such as pellet geometries, irregular geometries, and the like. For example, the marked consumable materials may be provided as pellets with one or more linear encodings formed on the exterior surfaces of the pellets as discussed above for filament **44**, filament **58**, and slug **74**. Examples of suitable pellet geometries include pellets having length-to-cross section (e.g., length-to-diameter) ratios ranging from about 1:1 to about 10:1. In some embodiments, suitable length-to-cross section ratios range from about 2:1 to about 5:1. The pellets may also include random fractured portions, such as random fractured ends.

[0105] Examples of suitable average cross sectional areas for the pellets range from about 0.2 square-millimeters to about 15 square-millimeters, with particular suitable average cross sectional areas ranging from about 0.75 square-millimeters to about 5 square millimeters. In embodiments in which the pellets have somewhat cylindrical cross sections, examples of suitable average diameters range from about 0.5 millimeters to about 4 millimeters, with particularly suitable average diameters ranging from about 1 millimeter to about 2 millimeters. Examples of suitable average lengths for the pellets range from about 1 millimeter to about 20 millimeters, with particularly suitable average lengths ranging from about 2 millimeters to about 10 millimeters.

[0106] FIG. **5** is a flow diagram of method **86** for manufacturing the marked consumable materials of the present disclosure, such as filament **44** (shown in FIG. **2**), filament **58** (shown in FIG. **3**), and slug **74** (shown in FIG. **4**). Method **58** includes steps **88**-**98**, and initially involves providing a consumable material precursor, which is the consumable material in an unmarked state (step **88**). For example, the precursor may be provided as a prefabricated material (e.g., filament or slug) in a solid state (e.g., retained on a supply source). Alternatively, the precursor may be provided by extruding the modeling or support material to form the precursor.

[0107] Examples of suitable techniques for forming the precursor for filament **44** include those disclosed in Comb. et al., U.S. Pat. Nos. 6,866,807 and 7,122,246. Examples of suitable techniques for forming the precursor for filament **58** include those disclosed in Batchelder et al., U.S. Pat. No. 8,221,669. Examples of suitable techniques for forming the precursor for slug **74** include those disclosed in Batchelder et al., U.S. Pat. No. 5,764,521. Additional examples of suitable techniques for forming the precursor with topographical surface patterns configured to engage with a filament drive mechanism of system **10** include those disclosed in Batchelder et al., U.S. Pat. No. 8,236,227.

[0108] The information to be written to the precursor as encoded markings may also be provided (step **90**). For example, the information may be retained in one or more computer systems prior to being written to the precursor. In one embodiment in which the information includes physical properties of the precursor, such as the local filament cross-sections (e.g., diameters and root-mean-square variations) and/or volume increments, this information may be obtained by measuring the precursor and storing the measurements in

one or more computer systems prior to being written to the precursor as encoded markings. For example, after the precursor of filament **44** is extruded and solidified, the diameters of successive portions of filament **44** may be measured and stored for subsequent writing as at least a portion of encoded markings **50**. Correspondingly, after the precursor of filament **58** is extruded and solidified, the cross-sectional areas of successive portions of filament **58** may be measured and stored for subsequent writing as at least a portion of encoded markings **68**.

[0109] The encoded markings (e.g., encoded markings **50**, **68**, and **84**) may then be formed at the exterior surface while the precursor is at least partially solidified (step **92**). In one embodiment, the encoded markings are formed at the exterior surface while the precursor is fully solidified. The pattern of the encoded markings may be based on the information being written, the encoding scheme used, and the device used to mark the precursor. A variety of encoding schemes may be used, where the encoding scheme desirably allows the encoded markings to be written to the precursor without substantially reducing line speeds. Examples of suitable average line speeds for manufacturing the marked consumable materials include line speeds up to about 20 meters/second (about 750 inches/second), with particularly suitable average line speeds ranging from about 1.3 meters/second (about 50 inches/second) to about 5 meters/second (about 200 inches/second). Additionally, the encoding scheme also desirably allows the encoded markings to be read by sensor assembly **24** or **26** in system **10** without substantially affecting the drive rate of the marked consumable material to extrusion head **18**.

[0110] In embodiments in which the encoded markings at least partially denote volume increments along the consumable material (e.g., filaments **50** and **68**, and slug **74**), the encoded markings may be formed at the exterior surface using a variety of different techniques based on the volume increments. For example, as discussed above, the encoded markings may be marked with the use of a phase-lock-loop (PLL) control system, where the phases of the output marking locations along the length may be varied based on input diameter or cross-sectional area measurements.

[0111] As also discussed above, controlling the operation of system **10** based on the read volume increments provides greater control over the extrusion properties of the consumable materials, and may compensate for variations in the diameters or cross-sectional areas of the consumable materials. As such, system **10** may extrude precise volumes of the consumable materials from liquefier assembly **34***a* (or liquefier assembly **34***b*), resulting in better part quality in 3D model **28** and/or support structure **30**.

[0112] As discussed above, the encoded markings may be formed by jetting materials that are not readily visible to the naked eye but may be detected using a non-visible wavelength (e.g., ultraviolet-activated materials). Alternatively, encoded markings **50**, **68**, and **84** may be formed as trench-based markings in the precursor. The trenches may be formed within the exterior surface of the precursor using a variety of techniques, such as laser ablation, physical imprinting, chemical etching (e.g., with masking), and combinations thereof. Due to the small dimensions and materials of the precursor, the particular technique used to form the trenches of the encoded markings is desirably selected to reduce the risk of significantly damaging or cracking the precursor while forming the trenches. As discussed below, the edges of the trench marks are suitable regions for scattering light in a darkfield illumination, which may allow an optical sensor assembly to read the encoded markings based on the patterns of the scattered light.

[0113] A suitable laser ablation technique for forming the encoded markings as trenches in the exterior surface of the precursor may be performed with an ultraviolet laser, such as an excimer laser. An excimer laser may remove material from the exterior surface of the precursor without significant damage or cracking to the underlying material of the precursor. Furthermore, excimer light may be strongly absorbed such that the surface material may be converted to vapor, leaving a trench without micro-cracks or residual ash. This embodiment is also beneficial for forming the encoded markings in a continuous manner, in which successive portions of the precursor may be exposed to the excimer laser.

[0114] Alternatively, the encoded markings may be formed with a variety of different processes. In one embodiment, the encoded markings may be formed with one or more coating processes, which may form the encoded markings on the exterior surface of the precursor as coatings that may be optically detected. For example, the coatings may be formed with a jetting, deposition, or evaporation process, where the coating is desirably formed with a material that is not readily visible to the naked eye but may be detected using a non-visible wavelength (e.g., ultraviolet-activated materials). In these embodiments, the sensor assembly (e.g., sensor assemblies **24** and **26**) may emit light in one or more non-visible wavelengths and detect the light emitted from the activated materials of the encoded markings. These embodiments are beneficial for reducing the impact of the encoded markings on the colors of the modeling and support materials.

[0115] In additional alternative embodiments, the encoded markings may be formed by one or more mechanical impression processes, such as by mechanically impressing the pattern into the surface, such as with an agile stylus, rotating die, a recycling belt, and the like. The exterior surface may also be machined, skived, ground, polished, and the like. Furthermore, the encoded markings may be produced by one or more surface property modification processes, such as by modifying the surface properties of the precursor material. For example, the degree of cross linking of the precursor material may be locally modified by ultraviolet light to varying the index of refraction. In this embodiment, the encoded markings may be generated as lines (e.g., parallel lines) of cross-linked precursor material having different indices of refraction from the remaining surface of the consumable material. As discussed below, this embodiment is particularly suitable for use as diffraction gratings with a sensor assembly configured to read information based on far-field diffraction patterns generated from the diffraction gratings. Ion implantation can similarly modify the local complex index.

[0116] After a particular segment of the precursor is marked with the encoded markings to form the marked consumable material, the recently formed encoded markings may optionally be read with a sensor assembly to ensure that the information in the encoded markings is accurate (step **94**). If the information is determined to be accurate, the marked consumable material may optionally undergo one or more post-processing operations (step **96**), and then may be loaded into or onto a supply source (e.g., supply sources **20** and **22**) for subsequent use in an additive manufacturing system (e.g., system **10**) (step **98**). In alternative embodiments, steps **94**, **96**, and **98** may be performed in different orders and/or one or both of steps **94** and **96** may be omitted.

[0117] FIG. **6** is a schematic illustration of marking system **100**, which is an example of a suitable laser marking system for forming encoded markings in a consumable material precursor, pursuant to step **92** of method **86** (shown in FIG. **5**). The following discussion of marking system **100** is made with reference to filament **44** (shown in FIG. **2**) with the understanding that marking system **100** may also be modified for forming encoded markings for a variety of marked consumable materials of the present disclosure (e.g., filament **58** shown in FIG. **3**, and slug **74** shown in FIG. **4**).

[0118] As shown in FIG. **6**, marking system **100** is a laser ablation system (e.g., an excimer laser ablation system) that includes laser source **102**, encoder mask **104**, beam splitter **106**, reflectors **108**, and slot apertures **110**. Laser source **102** is a laser emission source (e.g., an excimer laser source) for emitting laser beam **112** toward dielectric mask **104**. In one embodiment, laser source **102** is configured to emit laser beam **112** having an ultraviolet-radiation wavelength. In another embodiment, the wavelength for laser beam **112** ranges from about 100 nanometers to about 400 nanometers. In yet another embodiment, the wavelength for laser beam **112** ranges from about 150 nanometers to about 300 nanometers.

[0119] Laser source **102** also desirably emits laser beam **112** with an energy level that is sufficient to form the trenches of encoded markings **50** in the material of the precursor for filament **44**, while also desirably being low enough to reduce the risk of significantly damaging or cracking the precursor while forming the trenches. Examples of suitable energy levels per pulse of laser beam **112**, based on a pulse length of about 8 nanoseconds, range from about 4 millijoules to about 20 millijoules, with particularly suitable energy levels ranging from about 8 millijoules to about 15 millijoules.

[0120] Laser source **102** also desirably emits pulses of laser beam **112** with sufficient frequencies to form trenches of encoded markings **50** along successive portions of the precursor of filament **44** while maintaining a suitable line speed for filament **44**. Examples of suitable pulse frequencies for laser beam **112** range from about 500 hertz to about 1,500 hertz.

[0121] Encoder mask **104** is a mask configured to selectively form encoded marks **50** in filament **44** with laser beam **112** based on an encoding scheme. Examples of suitable encoder masks for encoder mask **104** include fixed and rotary-disk dielectric masks, such as chrome-on-fluoride masks (e.g., glass and quartz-based masks), which may contain coded patterns. For example, a rotary disk mask may contain radially coded patterns, where the timing of the pulse of laser beam **112** may select which encoded pattern is illuminated for imprinting onto filament **44**.

[0122] Beam splitter **106** is configured to split laser beam **112** into separate laser beams (referred to as laser beams **112***a*, **112***b*, and **112***c*) for forming encoded patterns **50***a*, **50***b*, and **50***c* in filament **44**. Reflectors **108** are reflective surfaces (e.g., dielectric mirrors) configured to reflect laser beams **112***a* and **112***c* back toward filament **44**. Slot apertures **110** are spaced around filament **44** and are configured to limit the radial dimensions of encoded patterns **50***a*, **50***b*, and **50***c*.

[0123] During operation, the precursor of filament **44** may be fed through slot apertures **110**, as shown. The information to be written to the precursor may then be encoded by a computer system (not shown) in signal communication with system **100**. Based on the encoding scheme used, the computer system may direct laser source **102** pulse laser beam **112** toward encoder mask **104**. The encoded pattern in encoder mask **104** may vary the patterns of laser beam **112** that pass through encoder mask **104** to beam splitter **106**. Beam splitter **106** splits the portion of laser beam **112** that passed through encoder mask **104** into laser beams **112***a*, **112***b*, and **112***c*. Laser beams **112***a*, **112***b*, and **112***c* may then be directed to exterior surface **48** of the precursor of filament **44** to desirably form trenches in the precursor based on the laser beam pattern.

[0124] For example, an energy pulse of about 12 millijoules may form a trench by removing about 1.2 square millimeters (about 1,900 square mils) of a polymer (e.g., ABS) to depth of about 2.5 micrometers (about 0.1 mils). If laser beam **112** is used to form trenches that are about 0.2 millimeters (about 8 mils) wide (e.g., width **56**) and about 2.5 millimeters (about 100 mils) long (e.g., length **54**) with a pulse frequency of about 1,000 hertz, encoded markings **50** may be formed in the precursor at a line speed greater than about 2.5 meters/second (about 100 inches/second). As such, system **100** may be used in a continuous process with the extrusion and formation of the precursor of filament **44**. The marking process may continue as successive portions of the precursor pass through system **100**, thereby forming successive trenches of encoded markings **50** along length **46**. The resulting filament **44** may then subjected to one or more additional steps of method **86** (e.g., steps **94**, **96**, and **98**), as discussed above.

[0125] While marking system **100** is described above as a suitable technique for forming trenches in filaments, in alternative embodiments, marking system **100** may be configured to form cross-linked markings in the surface of filament **44**. For example, the beams of ultraviolet light may cross-link the precursor material of filament **44** to vary the index of refraction at the locations of the encoded markings. This is particularly suitable in which the encoded markings function as diffraction gratings.

[0126] As discussed above, the marked consumable materials of the present disclosure allow information to be recorded in the consumable materials themselves. The encoded markings may contain a variety of information relating to the marked consumable materials and/or to the operations of the additive manufacturing systems (e.g., system **10**). Additionally, the sensor assemblies (e.g., sensor assemblies **24** and **26**) are configured to read the encoded markings from successive portions of the marked consumable materials as the marked consumable materials are fed to the additive manufacturing systems. This allows the additive manufacturing systems to use the information in the encoded markings for a variety of different purposes, such as for building 3D models and/or support structures.

[0127] As also discussed above, sensor assemblies **24** and **26** (shown in FIG. **1**) may be retained partially or fully within supply sources **20** and **22** (shown in FIG. **1**), respectively. For example, in one embodiment, sensor assembly **24** may include a first subassembly retained within system **10** at bay **20***a*, and a second subassembly retained within supply source **20**. In this embodiment, the first and second subassemblies may engage with each other when supply source **20** is loaded to bay **20***a* of system **10**. Sensor assembly **26** may also include the same arrangement for bay **22***a* and supply source **22**.

[0128] FIGS. **7-12** illustrate sensor assembly **200** in use with spooled container **202**, where sensor assembly **200** is an example of a suitable optical sensor assembly for use in system **10** (e.g., as sensor assembly **24** and/or sensor assembly **26**, shown in FIG. **1**). As shown in FIG. **2**, spooled con-

tainer **202** is a supply source containing filament **204**, where filament **204** is a marked filament. Examples of suitable marked filaments for filament **204** include those discussed above (e.g., filaments **44** and **58**).

[0129] Examples of suitable sources for spooled container **202** include those discussed above for supply sources **20** and **22** (shown in FIG. **1**), such as those disclosed in Swanson et al., U.S. Pat. No. 6,923,634; Comb et al., U.S. Pat. No. 7,122,246; Taatjes et al, U.S. Patent Application Publication Nos. 2010/0096485 and 2010/0096489; and Swanson, U.S. patent application Ser. No. 12/811,411 and International Publication No. WO2009/088995. In the shown embodiment, filament **204** may be wound around spool **206**, which correspondingly may be retained in container housing **208**. This arrangement allows filament **204** to be unwound from spool **206** while spool **206** rotates around hub **210** within container housing **208**, as represented by arrows **212**. Filament **204** may then pass through sensor assembly **200** and exit spooled container **202** to a pathway of system **10** (e.g., pathways **36** and **40**), as represented by arrow **214**.

[0130] Sensor assembly **200** includes subassemblies **216** and **218**, which, in the shown embodiment, are separate components that may engage with each other during a build operation. Subassembly **216** is retained within system **10**, outside of spooled container **202**, and contains the sensor electronics (not shown in FIG. **7**) for reading the encoded markings of filament **204**. Subassembly **218** is retained at least partially within container housing **208** of spooled container **202**, and is the portion that filament **204** passes through prior to exiting spooled container **202**. In the shown embodiment, subassembly **218** is fully retained within container housing **208**. As discussed below, when spooled container **202** is loaded into a bay of system **10** (e.g., bays **20***a* and **22***a*), subassembly **216** may engage with subassembly **218** to read encoded markings of filament **204** as successive portions of filament **204** pass through subassembly **218**.

[0131] As shown in FIG. **8**, subassembly **216** includes base block **220**, circuit board **222**, and waveguides **224**. Base block **220** is a structural mount for retaining circuit board **222**. In alterative embodiments, base block **220** may be omitted and circuit board **222** may be directly mounted within system **10**. Circuit board **222** is a control circuit for subassembly **216** and is configured to optically read the encoded markings of filament **204** as filament **204** passes through subassembly **218** within spooled container **202**. Circuit board **222** also desirably communicates with controller **32** over a communication line (e.g., communication line **226**), as discussed above for communication lines **38** and **42** (shown in FIG. **1**).

[0132] Waveguides **224** are a pair of waveguides (a single waveguide **224** is shown in FIG. **8**), which may be fabricated as an integral unit from a transparent or translucent plastic or glass material. Waveguides **224** are configured to route light from one or more light sources (not shown in FIG. **8**) mounted on circuit board **222** to subassembly **218**, as discussed below. Waveguides **224** are also configured to extend into an opening within container housing **208** (referred to as opening **228**) to engage subassembly **218**.

[0133] As further shown in FIG. **8**, subassembly **216** is biased in the direction of arrow **230** toward subassembly **218** by biasing members **232**. Biasing members **232** are one or more devices configured to bias subassembly **216** toward subassembly **218** when spooled container **202** is loaded to system **10**. In the shown embodiment, biasing members **232** are loaded springs located between base block **220** and the sidewall of the bay in which supply source **202** is loaded (referred to as sidewall **234**). In alternative embodiments, subassembly **216** may be mounted and biased from any suitable location within system **10**.

[0134] System **10** may also include one or more latching mechanisms (not shown) for retaining subassembly **216** in a retracted state against sidewall **234**. In these embodiments, subassembly **216** may remain in the retracted state while spooled container **202** is being loaded or unloaded from the bay of system **10**. When spooled container **202** is loaded to the bay, the latching mechanism may be released, thereby allowing subassembly **216** to engage subassembly **218**.

[0135] Subassembly **218** includes window **236**, waveguides **238**, and filament guide **240**, which may be fabricated as an integral unit from a transparent or translucent plastic or glass material. Window **236** may be secured to container housing **208** at opening **228**, which allows waveguides **224** of subassembly **216** to rest against window **236** at opening **228** due to the bias in the direction of arrow **230**. Waveguides **238** are a pair of waveguides (a single waveguide **238** is shown in FIG. **8**) configured to route light from waveguide **224** to filament guide **240**. As discussed below, filament guide **240** includes a channel for filament **204** to pass through while being fed from spooled container **202** to system **10**. The biasing of waveguides **224** against window **236** also allows the focal length of sensor assembly **200** to be repeatably fixed. This arrangement allows the light routed through waveguides **224** to also be routed through waveguides **238** to filament guide **240**, thereby providing a darkfield illumination for filament **204**.

[0136] As discussed below, the trench edges of the encoded markings of filament **204** scatter the light of the darkfield illumination in patterns based on the encoded markings. The scattered light may be optically detected at subassembly **216**, thereby allowing the information retained in the encoded markings to be read based on the patterns of the scattered light. Subassembly **216** may then transmit signals relating to the information to controller **32** over communication line **226**.

[0137] In one embodiment, subassembly **218** may form a moisture barrier with container housing **208**, allowing the interior of container housing **208** to retain a low moisture content. As shown, filament guide **240** includes inlet end **242** and outlet end **244**. Inlet end **242** desirably forms a first moisture barrier with the interior walls of container housing **208**, which define an interior region in which spool **206** may be retained (referred to as interior walls **246**).

[0138] In some embodiments, spooled container **202** may include one or more liners in addition to, or as an alternative to interior walls **246**. Examples of suitable liners include those disclosed in Swanson, U.S. Pat. No. 8,403,658 and International Publication No. WO2009/088995. In these embodiments, the liner may partially or fully encase spool **206** and may be secured around inlet end **242** of filament guide **240** to maintain a moisture barrier within container housing **208**.

[0139] Correspondingly, outlet end **244** desirably forms a second moisture barrier with the exterior walls of container housing **208** (referred to as exterior walls **248**) at the exit orifice of container housing **208** (referred to as exit orifice **250**). The pathway of system **10** to extrusion head **18** (e.g., pathways **36** and **40**, not shown in FIG. **8**) may also form a

moisture barrier at exit orifice **250** to maintain the low moisture environment between spooled container **202** and extrusion head **18**.

[0140] The moisture barriers formed between container housing **208** and filament guide **240** of subassembly **218** allow the interior region of spooled container **202** to be maintained at a low humidity level to reduce the absorption of water into filament **204**. Spooled container **202** may also include desiccant packs (not shown) within the interior region to maintain a dry environment. These implementations may allow filament **204** to maintain a low moisture content (e.g., less than about 700 parts-per-million by weight) during storage and use.

[0141] FIG. **9** is a bottom perspective view of sensor assembly **200**, where spooled container **202** and base block **220** are omitted for ease of discussion. As shown, waveguides **224** are a first pair of waveguides that are integrally connected at bridge **252**. As further shown, subassembly **216** also includes optical sensor **254**, which may be secured to circuit board **222**, as shown. Optical sensor **254** is a sensor configured to detect light scattered from the encoded markings of filament **204**. Examples of suitable units for optical sensor **254** include one or more imaging devices, such as a complementary metal-oxide-semiconductor (CMOS) camera.

[0142] Optical sensor **254** desirably exhibits imaging capabilities to detect the scattered light patterns from the encoded markings of filament **204**. Suitable imaging capabilities may vary depending on the light intensity of the darkfield illumination, the encoding scheme used, and the dimensions of the encoded markings. For example, an marking pattern of multiple marks having a length of about 2.5 millimeters may be imaged with a 2:1 magnification onto a 640×480 pixel array. Examples of suitable commercially available CMOS cameras and corresponding image processors for circuit board **222** and optical sensor **254** include those from Aptina Imaging Corporation, Grand Cayman, Ky.; and those from Toshiba Corporation, Minato, Tokyo, Japan.

[0143] As discussed below, subassembly **216** also includes a plurality of light sources (not shown in FIG. **9**) mounted on circuit board **222** at indentations in waveguides **224** adjacent to circuit board **222** (referred to as indentations **256**). In alternative embodiments, the light sources may be mounted at any suitable location within system **10**.

[0144] Waveguides **238** are a second pair of waveguides that are integrally connected at bridge **258**, where bridge **258** includes opening **260**. Opening **260** provides an access location for the light reflected from filament **204** (including the light scattered from the encoded markings of filament **204**) to transmit through to reach optical sensor **254**. As discussed below, one or more lenses may also be located between optical sensor **254** and opening **260** for increasing or otherwise modifying the focus and magnification of the transmitted light.

[0145] As shown, when subassembly **216** engages subassembly **218**, waveguides **224** substantially align with waveguides **238** along the x-axis. This allows the light routed through waveguides **224** to pass through window **236** to waveguides **238**. Waveguides **238** also route the received light, and the opposing end of waveguides **238** converge toward each other around filament guide **240**. This causes the routed light to reflect at least once prior reaching filament **204** to provide a darkfield illumination, as discussed below.

[0146] FIG. **10** is an exploded perspective view of subassembly **216**. As shown, bridge **252** of waveguides **224** includes opening **262**, which desirably aligns with opening **260** (shown in FIG. **9**) when subassembly **216** engages subassembly **218**. As discussed above, one or both of openings **260** and **262** may retain one or more lenses for increasing or otherwise modifying the focus and magnification of the transmitted light.

[0147] As further shown in FIG. **10**, light sources **264** are mounted to circuit board **222** and desirably align with indentations **256** of waveguides **224**. Light sources **264** may be any suitable type of light source to provide a darkfield illumination for filament **204**, such as light emitting diodes (LEDs). Additionally, while shown as two pairs of LEDs, subassembly **216** may include a variety of different numbers of light sources for providing a darkfield illumination for filament **204**. In one embodiment, light sources **264** may include multiple color LEDs, such as red, green, and blue LEDs, which may be selectively used to illuminate filament **204**.

[0148] FIG. **11** is a perspective view of subassembly **218**. As shown, window **236** of subassembly **218** also includes opening **266**, which is aligned with opening **260** (shown in FIG. **9**), and desirably aligns with opening **262** (shown in FIG. **10**) when subassembly **216** engages subassembly **218**. Openings **266** may also retain one or more lenses for increasing or otherwise modifying the focus and magnification of the transmitted light.

[0149] FIG. **12** is a bottom view of sensor assembly **200**, where subassembly **216** is engaged with subassembly **218**. During operation, filament **204** may be fed through the channel of filament guide **240** (referred to as channel **268**). Channel **268** desirably has dimensions that allow filament **204** to pass through filament guide **240** without undue friction while also desirably confining filament **204** to the object plane of optical sensor **254** such that the grazing angle input light scatters from the encoded markings of filament **204**.

[0150] In embodiments in which filament **204** is a marked cylindrical filament (e.g., filament **44**), suitable average inner diameters for channel **268** range from about 1.0 millimeter (about 0.04 inches) to about 3.8 millimeters (about 0.15 inches), and with particularly suitable average diameters ranging from about 1.3 millimeters (about 0.05 inches) to about 2.5 millimeters (about 0.1 inches).

[0151] In embodiments in which filament **204** is a marked non-cylindrical filament (e.g., filament **58**), channel **268** may include a cross section that substantially matches the geometry of the marked non-cylindrical filament. For example, in embodiments in which the marked non-cylindrical filament has a rectangular cross section (e.g., filament **58**), channel **268** desirably has a rectangular cross section with a width-to-thickness aspect ratio that substantially matches the aspect ratio of the filament. In these embodiments, suitable average widths for channel **268** range from about 1.3 millimeters (about 0.05 inches) to about 12.7 millimeters (about 0.50 inches), with particularly suitable average widths ranging from about 3.8 millimeters (about 0.15 inches) to about 10.2 millimeters (about 0.40 inches). Suitable average thicknesses for channel **268** range from about 0.25 millimeters (about 0.01 inches) to about 2.5 millimeters (about 0.1 inches), with particularly suitable average thicknesses ranging from about 0.51 millimeters (about 0.02 inches) to about 1.8 millimeters (about 0.07 inches).

[0152] The encoding scheme used desirably allows the encoded markings to be read by sensor assembly **200** without substantially affecting the drive rate of filament **204** to extrusion head **18**. The drive rate of filament **204** to extrusion head

18 may vary depending the extrusion parameters in extrusion head **18** and the dimensions of filament **204**. Examples of suitable drive rates range from about 2.5 millimeters/second (about 100 mils/second) to about 7.6 millimeters/second (about 300 mils/second).

[0153] As filament **204** passes through channel **268**, light is emitted from light sources **264**, which are routed through waveguides **224** and **238** toward filament guide **240**. The converging orientations of waveguides **238** desirably cause the routed light to reflect at least once prior reaching filament **204** to provide a darkfield illumination. In particular, the light desirably reflects at least once before grazing the exterior surface of filament **204** within filament guide **240**. When particular rays of the light reach the trench edges of the encoded markings of filament **204**, the trench edges cause these particular rays to scatter. Accordingly, the scattering of the light follows the pattern of the encoded markings.

[0154] A portion of the reflected and scattered light may then transmit through openings **266**, **260**, and **262** (and through any lenses retained therein) toward optical sensor **254**. Optical sensor **254** may image the received light, which, which may then be processed by circuit board **222** and/or controller **32** (via communication line **226**) to decode the information from the image patterns based on the encoding scheme used. Controller **32** may then use the received information to assist in the operation to build 3D model **28** and/or support structure **30**, as discussed above.

[0155] In another embodiment, the sensor assemblies may be retained fully within supply sources **20** and **22**, respectively. For example, FIG. **13** illustrates sensor assembly **300** in use with spooled container **302**, where sensor assembly **300** is an example of a suitable sensor assembly for use in system **10** (e.g., as sensor assembly **24** and/or sensor assembly **26**, shown in FIG. **1**). As shown, spooled container **302** is a supply source containing filament **304**, where filament **304** is a marked filament. Examples of suitable marked filaments for filament **304** include those discussed above (e.g., filaments **44** and **58**). In the shown example, spooled container is mounted in a bay of system **10** (e.g., bay **20***a*), which includes front wall **305**.

[0156] Examples of suitable sources for spooled container **302** include those discussed above for supply sources **20** and **22** (shown in FIG. **1**), such as those disclosed in Swanson et al., U.S. Pat. No. 6,923,634; Comb et al., U.S. Pat. No. 7,122,246; Taatjes et al, U.S. Patent Application Publication Nos. 2010/0096485 and 2010/0096489; and Swanson, U.S. Pat. No. 8,403,658 and International Publication No. WO2009/088995. In the shown embodiment, filament **304** may be wound around spool **306**, which correspondingly may be retained in container housing **308**. This arrangement allows filament **304** to be unwound from spool **306** while spool **306** rotates around hub **310** within container housing **308**, as represented by arrows **312**. Filament **304** may then pass through sensor assembly **300** and exit spooled container **302** to a pathway of system **10** (e.g., pathways **36** and **40**), as represented by arrow **314**.

[0157] In the shown embodiment, spooled container **302** also includes liner **316**, which includes one or more films configured to provide a moisture barrier within container housing **308**. Examples of suitable liners for liner **316** include those disclosed in Swanson, U.S. Pat. No. 8,403,658 and International Publication No. WO2009/088995.

[0158] As shown, sensor assembly **300** is fully retained within housing **308**, and within liner **316**. While sensor assembly **300** is illustrated in FIG. **13** as being located in a particular location within housing **308** and liner **316** (i.e., in an upper-left corner in the view shown in FIG. **13**), sensor assembly **300** may alternatively be disposed in other locations within housing **308** and liner **316** such that filament **304** may pass through (or adjacent to) sensor assembly **300** prior to exiting liner **316** and/or housing **308**.

[0159] Sensor assembly **300** may receive electrical power from and/or communicate with system **10** via signal lines **318** or other suitable power and/or signal communication techniques. For example, signal lines **318** may be arranged in an engagement manner as disclosed in one or more of Swanson et al., U.S. Pat. No. 6,923,634; Comb et al., U.S. Pat. No. 7,122,246; Taatjes et al, U.S. Patent Application Publication Nos. 2010/0096485 and 2010/0096489; and Swanson, U.S. Pat. No. 8,403,658 and International Publication No. WO2009/088995. In the shown embodiment, a portion of signal lines **318** desirably extends through liner **316** in a sealable manner that maintains the moisture barrier.

[0160] During use, filament **304** passes through sensor assembly **300** prior to exiting liner **316** and housing **308**. As such, sensor assembly **300** may read the encoded markings of filament **304** and transmit signals relating to the read markings to system **10**. Sensor assembly **300** may read the encoded markings of filament **304** using a variety of different techniques, which may vary depending on the particular marking techniques used to form the encoded markings along filament **304**.

[0161] FIG. **14** is a schematic illustration of a suitable embodiment of sensor assembly **300**, which is configured to read the encoded markings based on far-field diffraction patterns. As shown, in this embodiment, filament **304** includes encoded markings **320** formed on surface **322**, where the pattern of encoded markings **320** function as diffraction gratings having different indices of refractions from the remaining portions of surface **322**. Encoded markings **320** may be formed on or in surface **322** using one or more of the techniques discussed above. In one embodiment, the degree of cross linking of the precursor material may be locally modified by ultraviolet light to varying the index of refraction at the locations of encoded markings **320**.

[0162] As further shown, sensor assembly **300** includes light emitter **324** and optical detectors **326**. In alternative embodiments, sensor assembly **300** may include multiple light emitters and/or a different number of optical detectors **326**. In the shown embodiment, optical detectors **326** are desirably positioned such that diffracted beams of light from encoded markings **320** are directed to optical detectors **326**. The directions of the diffracted beams of light from encoded markings **320** may correspondingly be predetermined by the encoding pattern(s) of encoded markings **320**.

[0163] During operation, while successive segments of filament **304** pass through sensor assembly **300** in the direction of arrow **314**, light emitter **324** generates light beam **328** toward filament **304**. Encoded markings **320** are configured to diffract all or a portion of the incident light beam **328** into separate diffracted beams **330**. Diffracted beams **330** may be separately detected by optical detectors **326**, thereby generating electrical signals indicative of the information encoded in encoded markings **320**. The information may then be transmitted to controller **32** of system **10** (shown in FIG. **1**) over electrical connection lines **318** (shown in FIG. **13**) and communication line **36** or **40** (shown in FIG. **1**). Controller **32** may

then use the received information to assist in the operation to build 3D model **28** and/or support structure **30**, as discussed above.

[0164] FIG. **15** illustrates sensor assembly **400**, which is an example of a suitable sensor assembly for use in system **10** (e.g., as sensor assembly **24** and/or sensor assembly **26**, as shown in FIG. **2**) at a location downstream from supply source **20** or supply source **22** (shown in FIG. **2**). In this embodiment, sensor assembly **400** includes circuit board **402**, optical assembly **404**, light emitters **406**, lenses **408**, and optical detectors **410**, where optical assembly **404**, light emitters **406**, lenses **408**, and optical detectors **410** are secured to circuit board **402**. Sensor assembly **400** may also include a housing (not shown) to protect and function as a light shield for the interior components, such as optical assembly **404**, light emitters **406**, lenses **408**, and optical detectors **410**.

[0165] Circuit board **402** is a printed circuit board operably connected to controller **32** of system **10** (shown in FIGS. **1** and **2**) for relaying information and electrical power between sensor assembly **400** and controller **32**. Optical assembly **404** is a component through which a marked consumable material (e.g., filament) of the present disclosure may pass through when being fed from supply source **20** or **22** to extrusion head **18**, as discussed above for sensor assemblies **24** and **26** in FIG. **2**.

[0166] Optical assembly **404** is desirably transparent or translucent to allow light from light emitters **406** to pass through to the marked consumable material. Light emitters are configured to emit light to optical assembly **404** (e.g., ultraviolet light), as indicated by arrows **412**. The received light rays may reflect or otherwise emit from the marked consumable material based on the patterns of the encoded markings. For example, in embodiment in which the light rays are ultraviolet light rays and the encoded markings are derived from ultraviolet-activated materials (e.g., fluorescent materials), the ultraviolet-activated materials may emit activated light rays (e.g., fluorescent light) upon receiving the ultraviolet light rays.

[0167] Portions of the reflected or emitted light rays from the marked consumable material are directed to lenses **408**, as indicated by arrows **414**. Lenses **408** accordingly may redirect the received light rays toward optical detectors **410**, as indicated by arrows **416**. Optical detectors **410** may then generate electrical signals indicative of the information encoded in the encoded markings, which may then be transmitted to controller **32** communication line **36** or **40** (shown in FIG. **2**). Controller **32** may then use the received information to assist in the operation to build 3D model **28** and/or support structure **30**, as discussed above.

[0168] The use of four sets of lenses **408** and optical detectors **410** is suitable for detecting encoded markings located at any location on the exterior surface of the marked consumable material. In alternative embodiments, such as those in which the marked consumable material include multiple rows of the encoded markings (e.g., encoded markings separated by about 60 degree arcs around a cylindrical filament), sensor assembly **400** may include fewer sets of lenses **408** and optical detectors **410**.

[0169] As discussed above, the marked consumable materials of the present disclosure allow information to be recorded in the consumable materials themselves. The encoded markings may contain a variety of information relating to the marked consumable materials and/or to the operations of the direct digital or additive manufacturing systems (e.g., system **10**). Additionally, the sensor assemblies (e.g., sensor assemblies **24**, **26**, **200**, **300**, and **400**) are configured to read the encoded markings from successive portions of the marked consumable materials as the marked consumable materials are fed to the additive manufacturing systems. This allows the additive manufacturing systems to use the information in the encoded markings for a variety of different purposes, such as for building 3D models and/or support structures.

[0170] Although the present disclosure has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the disclosure.

1. An encoded filament for use in an additive manufacturing system having an extrusion head, the encoded filament comprising:

compositionally, a consumable material;

a longitudinal length;

volume-increment markings that are offset from each other along the longitudinal length of the encoded filament by increment lengths that vary to define segments of the encoded filament having volumes that are substantially the same, wherein the volume-increment markings are configured to be read by an optical sensor of the additive manufacturing system; and

a cross-sectional geometry configured to be received by a liquefier of the extrusion head for building a three-dimensional model from the consumable material.

2. The encoded filament of claim **1**, wherein the cross-sectional geometry comprises a substantially circular geometry having an average diameter ranging from about 0.8 millimeters to about 2.5 millimeters.

3. The encoded filament of claim **1**, wherein the cross-sectional geometry has a width and thickness, wherein the width of the cross-sectional geometry ranges from about 1.0 millimeter to about 10.2 millimeters, and wherein the thickness of the cross-sectional geometry ranges from about 0.08 millimeters to about 1.5 millimeters.

4. The encoded filament of claim **1**, wherein the volume-increment markings extend substantially along an entirety of the longitudinal length.

5. The encoded filament of claim **1**, wherein the consumable material comprises a thermoplastic material, and wherein the volume-increment markings comprise an ultraviolet-activated material.

6. The encoded filament of claim **1**, wherein the volume-increment markings comprise sub-marks denoting an encoding scheme for additional information.

7. The encoded filament of claim **7**, wherein the additional information in the sub-markings comprises local filament cross-sections, material type, material composition, manufacturing information for the encoded filament, product code, material origin information, or combinations thereof.

8. An encoded filament for use in an additive manufacturing system having an extrusion head, the encoded consumable filament comprising:

compositionally, a consumable material;

a longitudinal length;

volume-increment markings that are offset from each other along the longitudinal length of the encoded filament to define a plurality of segments of the encoded filament, wherein the plurality of segments of the encoded filament comprise:

a first segment having a first increment length and a first volume; and

a second segment having a second increment length and a second volume, wherein the first increment length is different from the second increment length, and the first volume is substantially the same as the second volume;

wherein the volume-increment markings are configured to be read by an optical sensor of the additive manufacturing system; and

a cross-sectional geometry configured to be received by a liquefier of the extrusion head for building a three-dimensional model from the consumable material.

9. The encoded filament of claim **8**, wherein the cross-sectional geometry comprises a substantially circular geometry having an average diameter ranging from about 0.8 millimeters to about 2.5 millimeters.

10. The encoded filament of claim **8**, wherein the cross-sectional geometry has a width and thickness, wherein the width of the cross-sectional geometry ranges from about 1.0 millimeter to about 10.2 millimeters, and wherein the thickness of the cross-sectional geometry ranges from about 0.08 millimeters to about 1.5 millimeters.

11. The encoded filament of claim **8**, wherein the volume-increment markings extend substantially along an entirety of the longitudinal length.

12. The encoded filament of claim **8**, wherein the consumable material comprises a thermoplastic material, and wherein the volume-increment markings comprise an ultraviolet-activated material.

13. The encoded filament of claim **8**, wherein the volume-increment markings comprise sub-marks denoting an encoding scheme for additional information.

14. The encoded filament of claim **13**, wherein the additional information in the sub-markings comprises local filament cross-sections, material type, material composition, manufacturing information for the encoded filament, product code, material origin information, or combinations thereof.

15. A method for manufacturing an encoded filament for use in building a three-dimensional model with an additive manufacturing system, the method comprising:

providing a filament compositionally comprising a consumable material, and having a longitudinal length and a cross-sectional geometry configured to be received by a liquefier of an extrusion head retained by the additive manufacturing system for building the three-dimensional model from the consumable material;

moving the filament at a predetermined line speed;

measuring cross-sectional dimensions along the longitudinal length of the moving filament; and

forming volume-increment markings along the longitudinal length on the moving filament by varying marking phase timings in response to the measured cross-sectional dimensions such that segments of the filament between each successively formed volume-increment marking have substantially the volume, wherein at least a portion of the segments of the filament have different increment lengths.

16. The method of claim **15**, wherein forming the volume-increment markings along the longitudinal length on the moving filament comprise forming the volume-increment markings with a phase-lock-loop control system.

17. The method of claim **15**, wherein the cross-sectional geometry comprises a substantially circular geometry having an average diameter ranging from about 0.8 millimeters to about 2.5 millimeters, and wherein measuring the cross-sectional dimensions along the longitudinal length of the moving filament comprise measuring diameters along the longitudinal length of the moving filament.

18. The method of claim **15**, wherein the cross-sectional geometry has a width and thickness, wherein the width of the cross-sectional geometry ranges from about 1.0 millimeter to about 10.2 millimeters, and wherein the thickness of the cross-sectional geometry ranges from about 0.08 millimeters to about 1.5 millimeters, and wherein measuring the cross-sectional dimensions along the longitudinal length of the moving filament comprise measuring at least one of widths and thicknesses along the longitudinal length of the moving filament.

19. The method of claim **15**, wherein the consumable material comprises a thermoplastic material, and wherein the volume-increment markings comprise an ultraviolet-activated material.

20. The method of claim **15**, wherein the volume-increment markings comprise sub-marks denoting an encoding scheme for additional information, and wherein the additional information in the sub-markings comprises local filament cross-sections, material type, material composition, manufacturing information for the encoded filament, product code, material origin information, or combinations thereof.

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