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(54) **Title**: APPARATUS AND METHOD FOR FORMING THREE-DIMENSIONAL OBJECTS USING A TILTING SOLIDIFICATION SUBSTRATE

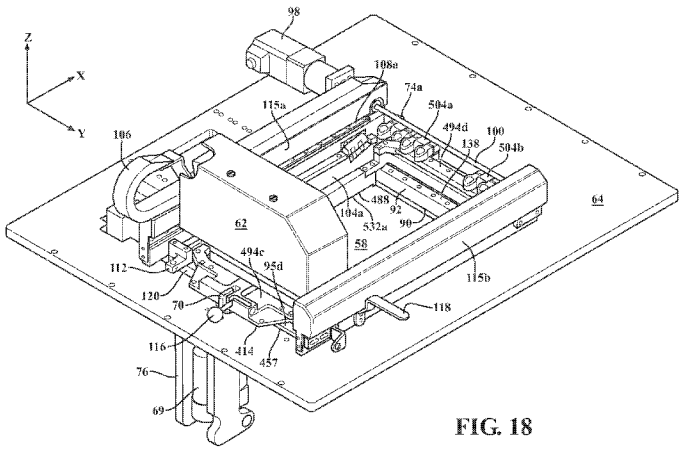


FIG. 18

(57) **Abstract**: An apparatus and method for making a three-dimensional object from a solidifiable material using a linear solidification device. The apparatus includes a solidification substrate that is tiltable relative to a film about a tilting axis. Layers of the solidifiable material solidify in contact with a film located between the most recently solidified object layer and a solidification substrate that comprises the solidification substrate assembly. The tilting of the solidification substrate relative to the film allows the substrate to be used to squeeze excess solidifiable material from between the film and the most recently solidified object surface while minimizing or eliminating the formation of bubbles in the solidifiable material which can prolong object build times. Additionally, tilting the solidification substrate before separating an adhered object surface from the film breaks any vacuum formed between the substrate and the film which reduce the forces involved in separating the object from the film.

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APPARATUS AND METHOD FOR FORMING THREE-DIMENSIONAL OBJECTS USING A TILTING SOLIDIFICATION SUBSTRATE

FIELD

[0001] The disclosure relates to an apparatus and method for manufacturing three-dimensional objects, and more specifically, to an apparatus and method that forms such objects using a tilting solidification substrate.

DESCRIPTION OF THE RELATED ART

[0002] Three-dimensional rapid prototyping and manufacturing allows for quick and accurate production of components at high accuracy. Machining steps may be reduced or eliminated using such techniques and certain components may be functionally equivalent to their regular production counterparts depending on the materials used for production.

[0003] The components produced may range in size from small to large parts. The manufacture of parts may be based on various technologies including photo-polymer hardening using light or laser curing methods. Secondary curing may take place with exposure to, for example, ultraviolet (UV) light. A process to convert a computer aided design (CAD) data to a data model suitable for rapid manufacturing may be used to produce data suitable for constructing the component. Then, a pattern generator may be used to construct the part. An example of a pattern generator may include the use of DLP (Digital Light Processing technology) from Texas Instruments®, SXRD™ (Silicon X-tal Reflective Display), LCD (Liquid Crystal Display), LCOS (Liquid Crystal on Silicon), DMD (digital mirror device), J-ILA from JVC, SLM (Spatial light modulator) or any type of selective light modulation system. Other examples of pattern generators include linear solidification devices that project solidification energy in a plurality of adjacent linear patterns, such as linear solidification devices that include a laser diode in optical communication with a rotating polygonal mirror. Further examples of pattern generators include systems with a laser in optical communication with galvanometer mirrors that draw linear or non-linear patterns of solidification energy on the exposed surface of solidifiable material.

[0004] In many known techniques of making a three-dimensional object from a solidifiable resin, such as a photocurable or photopolymerizable material, it is necessary to create a substantially planar exposed surface of the solidifiable resin in order to regulate the depth to which the solidification energy penetrates and solidifies the resin. One method involves placing a solidification substrate such as a plastic or glass that is translucent and/or transparent on the exposed surface of the resin and projecting solidification energy through the plastic or glass and into the resin. In a modified implementation, the solidification substrate comprises a film that is either coated on the plastic or glass or is stretched over the glass or plastic without adhering to it. While such systems create a planar exposed resin surface, they often also result in a bond forming between the newly exposed surface of the object and the solidification substrate which must be broken prior to forming a new object layer. These systems typically require some method or apparatus for separating the recently formed exposed object surface from the solidification substrate and for subsequently introducing fresh resin between the newly formed exposed object surface and the solidification substrate. Known techniques often introduce undesirable delays in the production of objects and/or increase the susceptibility of the part to damage, such as damage caused by forces from the surrounding resin applied against the part. Thus, a need has arisen for an apparatus and method for making three-dimensional objects which addresses the foregoing issues.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] The disclosure will now be described, by way of example, with reference to the accompanying drawings, in which:

[0006] FIG. 1A is a schematic view of an apparatus for making a three-dimensional object from a solidifiable material that comprises a tiltable solidification substrate assembly with the solidification substrate assembly in a level configuration prior to the solidification of the first layer of an object;

[0007] FIG. 1B is a schematic view of the apparatus of FIG. 1A in which a first layer of the three-dimensional object is formed on the build platform, and the solidification substrate assembly is in the level configuration of FIG. 1A;

[0008] FIG. 1C is a schematic view of the apparatus of FIG. 1A with the solidification substrate assembly in a tilted configuration relative to a work table and the build platform following an object peeling operation;

[0009] FIG. 1D is a schematic view of the apparatus of FIG. 1A with the solidification substrate assembly in the tilted configuration of FIG. 1C after the build platform has moved away from the solidification substrate assembly by one layer thickness to introduce unsolidified resin between the exposed object surface and the solidification substrate;

[0010] FIG. 1E is a schematic view of the apparatus of FIGS. 1A with the solidification substrate assembly in the level configuration of FIG. 1A depicting the squeezing out of resin from the space between the exposed object surface and the solidification substrate;

[0011] FIG. 2 is a close-up schematic view of the apparatus of FIGS. 1A-1E depicting the pressure forces applied on a pressure sensor placed on a work table;

[0012] FIG. 3 is a block diagram used to depict a controller suitable for use in the apparatus of FIGS. 1A-E in addition to various inputs to and outputs from the controller;

[0013] FIG. 4A is a detailed first perspective view of an exemplary solidification substrate assembly and a work table used in an apparatus for making a three-dimensional object from a solidifiable material with the solidification substrate assembly in a level configuration;

[0014] FIG. 4B depicts the apparatus of FIG. 4B with the solidification substrate assembly in a tilted configuration;

[0015] FIG. 4C is a close-up detailed view of a portion of the apparatus of FIGS. 4A-4B used to illustrate the connection between an actuator shaft and a load frame and the relationship between the load frame and a pressure (or force) sensor on the work table when the solidification substrate assembly is in a tilted configuration;

[0016] FIG. 4D is a detailed second perspective view of the apparatus of FIG. 4A with the solidification substrate assembly in a tilted configuration;

[0017] FIG. 4E is a detailed perspective view of the apparatus of FIG. 4B illustrating the connection between the distal end of the actuator and a load frame latch;

[0018] FIG. 5A is an exploded perspective view of a solidification substrate frame, a load frame, and a film assembly in an unassembled condition;

[0019] FIG. 5B is a side elevation view of FIG. 5A;

[0020] FIG. 5C is a perspective view of the solidification substrate frame, load frame, and film assembly of FIGS. 5A and 5B in an assembled condition;

[0021] FIG. 6 is a detailed perspective view of an exemplary solidification substrate assembly and work table used in an apparatus for making a three-dimensional object from a solidifiable material with the solidification substrate assembly in a level configuration;

[0022] FIG. 7 is a flow chart depicting a first method of making a three-dimensional object using an apparatus with a tiltable solidification substrate assembly;

[0023] FIGS. 8A and 8B are a flow chart depicting a second method of making a three-dimensional object using an apparatus with a tiltable solidification substrate assembly;

[0024] FIG. 9 is an exemplary depiction of data records from the tilting parameter database of FIG. 3;

[0025] FIG. 10 is a detailed perspective view of an alternative exemplary solidification substrate assembly and work table used in an apparatus for making a three-dimensional object from a solidifiable material with the solidification substrate assembly in a level configuration;

[0026] FIG. 11 is a view of the apparatus of FIGS. 10, with the solidification substrate assembly in an open configuration in which the tilting actuators are disconnected from the work table latches;

[0027] FIG. 12A is a detailed view of a left side of the work table, load frame, and solidification substrate of the apparatus of FIG. 10 showing a load frame bracket engaging the work table;

[0028] FIG. 12B is a detailed view of a right side of the work table, load frame, and solidification substrate of the apparatus of FIG. 12A showing a load frame bracket engaging a load cell used to indicate the force or pressure applied by the solidification substrate assembly against the work table;

[0029] FIG. 13 is a detailed view of an actuator and actuator support of the apparatus of FIG. 10 with a modified horizontal support structure;

[0030] FIG. 14A is a graph depicting one exemplary profile of the force applied by a motor-driven actuator to a solidification substrate assembly and the motor load during three phases of a method of making a three-dimensional object from a solidifiable material;

[0031] FIG. 14B is a graph depicting another exemplary profile of the force applied by a motor-driven actuator to a solidification substrate assembly and the motor load during three phases of a method of making a three-dimensional object from a solidifiable material;

[0032] FIG. 15 is a flow chart depicting a dual-mode method of making a three-dimensional object from an apparatus comprising a tiltable solidification substrate assembly;

[0033] FIG. 16A is a detailed perspective view of a modified version of the solidification substrate assembly and work table of FIGS. 4A-4E in which the film assembly has been replaced with a removable solidification substrate laminate, and the solidification substrate assembly is in an open configuration with the tilting actuator is disconnected from the work table latch;

[0034] FIG. 16B is a top perspective view of the apparatus of FIG. 16B with the solidification substrate assembly in a level condition during an object solidification operation;

[0035] FIG. 16C is an exploded assembly view of the solidification substrate laminate frame of FIG. 16A;

[0036] FIG. 16D is a perspective view of the solidification substrate laminate frame of FIG. 16C in an assembled condition;

[0037] FIG. 16E is a bottom perspective view of the solidification substrate laminate frame of FIG. 16C;

[0038] FIG. 16F is a close-up of a portion of the bottom of the solidification substrate laminate frame of FIG. 16C;

[0039] FIG. 17A is a first exemplary solidification substrate laminate;

[0040] FIG. 17B is a second exemplary solidification substrate laminate;

[0041] FIG. 17C is a third exemplary solidification substrate laminate;

[0042] FIG. 18 is a perspective view of an alternative embodiment of an apparatus for making a three-dimensional object which includes a solidification substrate assembly, load frame, film assembly, and work table in which a solidification substrate is tiltable relative to the film assembly showing the solidification substrate assembly in a level (untilted) configuration;

[0043] FIG. 19 is a perspective view of the embodiment of FIG. 18 with the solidification substrate assembly in a tilted configuration relative to the film assembly;

[0044] FIG. 20 is a detailed view of a portion of the embodiment of FIG. 18 showing a hinged connection between the solidification substrate assembly and the load frame;

[0045] FIG. 21 is a detailed view of a portion of the embodiment of FIG. 18 showing the solidification substrate frame latch and the actuator for tilting the solidification substrate frame;

[0046] FIG. 22 is a detailed view of the solidification substrate frame and solidification substrate of the embodiment of FIG. 18;

[0047] FIG. 23A is an exploded perspective view showing the relationship between the solidification substrate frame, load frame, and film assembly of FIG. 18;

[0048] FIG. 23B is an exploded side elevation view showing the relationship between the solidification substrate frame, load frame, and film assembly of FIG. 18;

[0049] FIG. 23C is a perspective view showing the solidification substrate frame, load frame, and film assembly of FIG. 18 in an assembled condition; and

[0050] FIG. 24 is a flow chart depicting a method of making a three-dimensional object using the apparatus of FIG. 18.

[0051] Like numerals refer to like parts in the drawings.

DETAILED DESCRIPTION

[0052] The Figures illustrate examples of an apparatus and method for manufacturing a three-dimensional object from a solidifiable material. Based on the foregoing, it is to be generally understood that the nomenclature used herein is simply for convenience and the terms used to describe the invention should be given the broadest meaning by one of ordinary skill in the art.

[0053] The apparatuses and methods described herein are generally applicable to additive manufacturing of three-dimensional objects, such as components or parts (discussed herein generally as objects), but may be used beyond that scope for alternative applications. The system and methods generally include a pattern generator that applies solidification energy to a solidifiable material, such as a photohardenable resin. The photohardenable resin solidifies in

contact with a solidification substrate, i.e., a surface against which solidification occurs. The solidification substrate may be a rigid or semi-rigid solidification substrate and/or a film.

[0054] In one aspect of the present disclosure, an apparatus for making a three-dimensional object is provided which includes a build platform that moves along a first axis, a solidification substrate assembly, an actuator operatively connected to the solidification substrate assembly, and at least one controller operatively connected to the actuator. The solidification substrate assembly includes a solidification energy source, a rigid or semi-rigid solidification substrate that is transparent and/or translucent, and a film assembly. When it receives an actuator activation signal from the at least one controller, the actuator tilts the solidification substrate assembly about a second axis. In a first optional modification, the apparatus includes a tilting parameter database comprising a plurality of solidifiable material identifiers, and a set of tilting parameters corresponding to each solidifiable material, wherein the set of tilting parameters includes at least one tilting parameter. In certain optional and preferred embodiments, the apparatus does not include a peeling member that contacts the solidification substrate to peel it from the exposed object surface.

[0055] The term "tilting parameter" refers to a variable that is used to control the tilting of a solidification substrate assembly. Exemplary tilting parameters include an actuator peeling distance, a minimum object peeling travel distance, a peeling velocity, a leveling velocity, a leveling wait time, and a leveling pressure controller set point. In a further variation of the first optional modification, at least one of the tilting parameters is determined based on the particular solidifiable material from which the three-dimensional object is made and/or object data representative of the three-dimensional object. In one example of this variation, the at least one tilting parameter is calculated for a plurality of layers or for each layer of the object based on the object data for the layer. As used herein, the phrase "minimum object peeling travel distance" refers to a minimum desired linear distance traveled during a tilting operation by a point of a solidification substrate that is initially in contact with a region of an exposed object surface that is closest to the axis of tilting. The phrase "actuator peeling distance" refers to a linear elongation of an actuator during a tilting operation. In certain examples herein, the actuator peeling distance will be a distance of travel of an actuator shaft (either a distal end or a proximal

end of the shaft) during a tilting operation. In other examples, the actuator peeling distance refers to a distance of travel of an actuator proximal housing end during a tilting operation. The terms "peeling velocity" and "leveling velocity" refer to the linear speed of travel of an actuator shaft (or the speed of travel of the actuator housing) during tilting operations conducted to peel a solidified object from a solidification substrate and to return the solidification substrate to a level configuration, respectively.

[0056] In another aspect of the present disclosure, an apparatus for making a three-dimensional object from a solidifiable material is provided which comprises a linear solidification device that is movable along a first axis while progressively supplying solidification energy along a second axis. The apparatus further comprises a rigid or semi-rigid solidification substrate that is transparent and/or translucent, an actuator operatively connected to the rigid or semi-rigid solidification substrate and operable to tilt the substrate about the second axis, and a build platform movable along a third axis. In an optional modification, the solidification substrate assembly also includes a film assembly, and the actuator is operatively connected to the film assembly and is operable to tilt the film assembly about the second axis. In the same optional modification or in a different one, the linear solidification device and the rigid or semi-rigid solidification substrate comprise a solidification substrate assembly, and the actuator is operatively connected to the solidification substrate assembly and operable to tilt the solidification substrate assembly about the second axis. In certain optional and preferred examples, the apparatus does not include a peeling member that contacts the solidification substrate to peel it from the exposed object surface.

[0057] In a further optional modification, at least one controller is operatively connected to the actuator. The at least one controller comprises a processor and a non-transitory computer readable medium having computer executable instructions stored thereon. When the computer executable instructions are executed by the processor, the at least one controller generates an actuator activation signal, and the actuator tilts the solidification substrate in response to the actuator activation signal. In the same or in another optional modification, the apparatus includes a tilting parameter database comprising a plurality of solidifiable material identifiers, and a plurality of sets of tilting parameters, each set corresponding to a solidifiable material

identifier, wherein each set of tilting parameters includes at least one tilting parameter. In a further variation of the first optional modification, at least one of the tilting parameters is determined based on the particular solidifiable material from which the three-dimensional object is made and/or object data representative of the three-dimensional object. In one example of this variation, the at least one tilting parameter is calculated for a plurality of layers or for each layer of the object based on the object data for the layer.

[0058] In a further aspect of the present disclosure, a method of making a three-dimensional object from a solidifiable material is provided which comprises providing a layer of the solidifiable material having an exposed surface adjacent a rigid or semi-rigid solidification substrate, wherein the rigid or semi-rigid solidification substrate is transparent and/or translucent. The method further comprises moving a linear solidification device along a first axis, progressively exposing portions of the layer of solidifiable material to solidification energy from the linear solidification device along a second axis as the linear solidification device moves along the first axis, and tilting the solidification substrate about the second axis. In one optional modification, the step of tilting the solidification substrate about the second axis comprises tilting the solidification substrate away from the build platform about the second axis, and moving the build platform in a direction away from the solidification substrate by a desired layer thickness. In the same or another optional modification, the step of tilting the solidification substrate about the second axis comprises selecting at least one tilting parameter based on the solidifiable material and tilting the solidification substrate about the second axis in accordance with the at least one tilting parameter. The tilting parameter may also be selected based on the object data in addition to or instead of selecting it based on the solidifiable material. In one example of this variation, the at least one tilting parameter is calculated for a plurality of layers or for each layer of the object based on the object data for the layer. In certain optional and preferred examples, the method does not comprise traversing a peeling member to contact the solidification substrate and peel it from the exposed object surface.

[0059] In yet another aspect of the present disclosure, a method of making a three-dimensional object from a solidifiable material is provided which comprises solidifying a portion of the solidifiable material to create an exposed solidified object surface in contact with a

solidification substrate, and tilting the solidification substrate about a first axis in accordance with at least one tilting parameter, wherein the at least one tilting parameter is based on at least one of object data representative of the three-dimensional object and the solidifiable material. In a first optional variation, the at least one tilting parameter is based on both object data representative of the object and the solidifiable material. In one example, the at least one tilting parameter for a given layer is determined based on the exposed object area defined by the object data for the layer. In another example, a first tilting parameter is provided which comprises a minimum object peeling travel distance, and a second tilting parameter which comprises an actuator peeling distance (i.e., a distance of extension or retraction by a tilting actuator used to carry out the tilting operation) is determined based on object data and/or the minimum object peeling travel distance. In certain optional and preferred examples, the method does not comprise traversing a peeling member to contact the solidification substrate and peel it from the exposed object surface. In other optional and preferred examples, the solidification substrate is rigid or semi-rigid and is transparent and/or translucent. In optional and preferred embodiments, the solidification substrate is a transparent and/or translucent resilient layer or protective film.

[0060] In an additional aspect of the present disclosure, a method of making a three-dimensional object from a solidifiable material is provided which comprises solidifying a first layer of the solidifiable material in a first pattern corresponding to a first portion of the three-dimensional object to form a first solidified exposed object surface in contact with a solidification substrate, wherein the first layer of the solidifiable material is located between a build platform and the solidification substrate along a build axis. The method also comprises first tilting the solidification substrate about a tilting axis in a direction away from the build platform, moving the build platform away from the solidification substrate within a volume of the solidifiable material to provide a second layer of solidifiable material between the solidified exposed object surface and the solidification substrate, second tilting the solidification substrate about the tilting axis in a direction toward the build platform; and solidifying the second layer of the solidifiable material in a second pattern corresponding to a second portion of the three-dimensional object. In certain optional and preferred examples, the solidification substrate is transparent and/or translucent and is a resilient layer, a film, or is rigid or semi-rigid. In other

optional and preferred examples, a tilting parameter database comprising sets of tilting parameters stored in association with solidifiable material identifiers is provided, and a tilting operation is carried out based on a tilting parameter from the tilting parameter database. In further optional and preferred examples, the solidification substrate assembly includes a source of solidification energy. In additional optional and preferred examples, the method does not comprise traversing a peeling member to contact the solidification substrate and peel it from the exposed object surface.

[0061] In certain examples, the apparatuses and methods described herein beneficially increase the speed of a method of making a three-dimensional object while preserving the integrity of the object. As described further below, in certain examples, the tilting apparatuses and methods also tailor the tilting process to object properties, such as exposed surface area and/or the location of the object relative to the axis of tilting, which may vary on a layer by layer basis so that only the required amount of tilting to affect part separation or to provide a stable layer of solidifiable material is performed.

[0062] In still another aspect of the present disclosure, a method of making a three-dimensional object is provided which comprises solidifying a layer of solidifiable material in contact with a solidification substrate laminate to create a portion of a three-dimensional object having an exposed object surface adhered to an object-contacting surface of the solidification substrate laminate. The three-dimensional object is disposed on a build platform, and the step of solidifying the solidifiable material comprises projecting solidification energy through an open top of a solidifiable material container that contains the layer of solidifiable material and which has a closed bottom. The method further comprises tilting the solidification substrate laminate about a tilting axis in a direction away from the build platform to separate the three-dimensional object from the solidification substrate laminate, lowering the build platform such that a next layer of solidifiable material flows over the exposed object surface, and tilting the solidification substrate laminate about the tilting axis in a direction toward the build platform. In certain examples, the solidification substrate laminate comprises a rigid or semi-rigid solidification substrate that is transparent and/or translucent and either or both of a resilient layer and a protective film.

[0063] In a further aspect of the present disclosure, an apparatus is provided which comprises a source of solidification energy, a solidifiable material container having a closed bottom and an open top, a build platform movable along a build axis and having an object build surface that faces the open top and the source of solidification energy, a solidification substrate assembly comprising one selected from a film assembly and a solidification substrate laminate, an at least one actuator operatively connected to the solidification substrate assembly which is operable to tilt the solidification substrate assembly about a tilting axis. In certain examples, the solidification substrate assembly comprises the solidification substrate laminate, and the solidification substrate laminate comprises a rigid or semi-rigid solidification substrate that is transparent and/or translucent, and either or both of a resilient layer and a protective film.

[0064] As discussed herein, a solidifiable material is a material that when subjected to energy, wholly or partially hardens. This reaction to solidification or partial solidification may be used as the basis for constructing the three-dimensional object. Examples of a solidifiable material may include a polymerizable or cross-linkable material, a photopolymer, a photo powder, a photo paste, or a photosensitive composite that contains any kind of ceramic based powder such as aluminum oxide or zirconium oxide or ytteria stabilized zirconium oxide, a curable silicone composition, silica based nano-particles or nano-composites. The solidifiable material may further include fillers. Moreover, the solidifiable material my take on a final form (e.g., after exposure to the electromagnetic radiation) that may vary from semi-solids, solids, waxes, and crystalline solids. In one embodiment of a photopolymer paste solidifiable material, a viscosity of between 10000 cP (centipoises) and 150000 cp is preferred.

[0065] When discussing a photopolymerizable, photocurable, or solidifiable material, any material is meant, possibly comprising a resin and optionally further components, which is solidifiable by means of supply of stimulating energy such as electromagnetic radiation. Suitably, a material that is polymerizable and/or cross-linkable (i.e., curable) by electromagnetic radiation (common wavelengths in use today include UV radiation and/or visible light) can be used as such material. In an example, a material comprising a resin formed from at least one ethylenically unsaturated compound (including but not limited to (meth)acrylate monomers and polymers) and/or at least one epoxy group-containing compound may be used. Suitable other

components of the solidifiable material include, for example, inorganic and/or organic fillers, coloring substances, viscose-controlling agents, etc., but are not limited thereto.

[0066] When photopolymers are used as the solidifiable material, a photoinitiator is typically provided. The photoinitiator absorbs light and generates free radicals which start the polymerization and/or crosslinking process. Suitable types of photoinitiators include metallocenes, 1,2 di-ketones, acylphosphine oxides, benzyldimethyl-ketals, α-amino ketones, and α-hydroxy ketones. Examples of suitable metallocenes include Bis (eta 5-2, 4-cyclopenadien-1-yl) Bis [2,6-difluoro-3-(1H-pyrrol-1-yl) phenyl] titanium, such as Irgacure 784, which is supplied by Ciba Specialty chemicals. Examples of suitable 1,2 di-ketones include quinones such as camphorquinone. Examples of suitable acylphosphine oxides include bis acyl phosphine oxide (BAPO), which is supplied under the name Irgacure 819, and mono acyl phosphine oxide (MAPO) which is supplied under the name Darocur® TPO. Both Irgacure 819 and Darocur® TPO are supplied by Ciba Specialty Chemicals. Examples of suitable benzyldimethyl ketals include alpha, alpha-dimethoxy-alpha-phenylacetophenone, which is supplied under the name Irgacure 651. Suitable α-amino ketones include 2-benzyl-2-(dimethylamino)-1-[4-(4-morpholinyl) phenyl]-1-butanone, which is supplied under the name Irgacure 369. Suitable α-hydroxy ketones include 1-hydroxy-cyclohexyl-phenyl-ketone, which is supplied under the name Irgacure 184 and a 50-50 (by weight) mixture of 1-hydroxy-cyclohexyl-phenyl-ketone and benzophenone, which is supplied under the name Irgacure 500.

[0067] Referring now to FIGS. 1A-1E, an apparatus 40 for making a three-dimensional object from a solidifiable material is depicted. The apparatus 40 includes a housing 42 in which a container 44 is disposed. The container 44 has a closed bottom 45 and an open top 47 and holds a volume of solidifiable material 50, which is preferably a photohardenable liquid or paste that solidifies upon exposure to solidification energy of an appropriate wavelength and intensity for a sufficient period of time. A three-dimensional object 78 (FIG. 1B) is progressively built upward on build platform 46 in the positive build (z) axis direction by supplying solidification energy from the linear solidification device 62 to the solidifiable material 50 during an object solidification operation. The solidification energy is supplied in geometric patterns that

correspond to object data, causing the solidifiable material to solidify in a shape corresponding to the object data.

[0068] At least one controller (not shown in FIGS. 1A-1E) is provided to selectively activate a solidification energy source in the linear solidification device 62 and to selectively energize a linear solidification device motor (not shown) that is operable to traverse the linear solidification device 62 along a travel (x) axis. Examples of linear solidification devices are described in FIGS. 3, 4, and 5A-5D of Applicant's co-pending U.S. Patent Application No. 13/534,638, filed on June 27, 2012 and the corresponding text, including at paragraphs 60-79 and 86-104, the contents of which are hereby incorporated by reference. Exemplary pattern generators other than linear solidification devices which may be used include DLP (Digital Light Processing technology) from Texas Instruments®, SXRD™ (Silicon X-tal Reflective Display), LCD (Liquid Crystal Display), LCOS (Liquid Crystal on Silicon), DMD (digital mirror device), J-ILA from JVC, SLM (Spatial light modulator) or any type of selective light modulation system. Pattern generators that "draw" laser energy in two-dimensionally varying patterns across an exposed surface of solidifiable material may also be used, such as those that comprise a laser in optical communication with x-y galvanometer mirrors. The linear solidification device 62 projects solidification energy through the open top 47 of solidifiable material container 44 as well as through rigid or semi-rigid solidification substrate 58 and film 60.

[0069] The object 78 is built on an upward facing surface (or object build surface) 48 of the build platform 46. Object 78 includes a build platform contacting surface 80 that rests on (and typically is adhered to) the object build surface 48 of build platform 46. The build platform contacting surface 80 typically comprises discrete, removable supports. The object build surface 48 faces the open top 47 of solidifiable material container 44 and linear solidification device 62. A vertically-movable shaft 52 is movable within the housing 42 to adjust the build (z) axis position of the build platform 46 relative to the work table 64. The bottom of the vertically-movable shaft 52 is contained within a bottom portion of the housing 42 which is not shown for ease of illustration. A build platform motor (not shown) is provided and is operable to move the build platform 46 along the build (z) axis. At least one controller (not shown) is operatively connected to the build platform motor to selectively operate it in accordance with computer

executable instructions stored in the non-transitory memory of the at least one controller and executed by the processor of the at least one controller. In certain examples herein, when executed by the processor, the computer executable instructions cause the build platform 46 to move downward along the build (z) axis by a defined layer thickness Δz following the solidification of a layer of the solidifiable material.

[0070] The apparatus 40 also includes a solidification substrate assembly 57, which in the depicted embodiment includes a rigid or semi-rigid solidification substrate 58, a film 60, and a load frame 56. The film 60 has an object-contacting surface 61 which faces the closed bottom 45 of solidifiable material container 44. In the example of FIGS. 1A-1E, the solidification substrate assembly 57 also comprises the linear solidification device 62. The rigid or semi-rigid solidification substrate 58 is preferably transparent and/or translucent to solidification energy supplied by a source of solidification energy. In the example of FIGS. 1A-1E, the source of solidification energy is provided in a linear solidification device 62. Although not depicted in FIGS. 1A-1E, the linear solidification device 62 is attached to the load frame 56 via a pair of linear rails spaced apart from one another in the y-axis direction and along which a support member attached to the linear solidification device 62 slidably translates in the x-axis direction. As further illustrated in the examples of FIGS. 4A-6, the rigid or semi-rigid solidification substrate 58 may be provided in a separate frame that attaches to the load frame 56, and the film 60 may be provided in a film assembly that attaches to the load frame 56 or to a frame holding the rigid or semi-rigid solidification substrate 58. In either event, the rigid or semi-rigid solidification substrate 58 and film 60 are directly or indirectly attached to the load frame 56 and movable therewith. In the example of FIGS. 1A-1E, film 60 is not bonded or adhered to the rigid or semi-rigid solidification substrate 58 but may closely contact the substrate 58. However, in other examples, and as described below with reference to FIGS. 16A-16F and 17A-17C, instead of using a rigid or semi-rigid solidification substrate 58 and a separate film 60, a solidification substrate laminate 298 may be used. The solidification substrate laminate 298 may comprise a resilient layer and/or a protective film bonded to rigid or semi-rigid solidification substrate 58 to define an integral, layered structure. In that case, solidification substrate laminate

298 includes an object contacting surface 301 that faces the closed bottom 45 of solidifiable material container 44.

[0071] As indicated previously, solidifiable material 50, such as a photohardenable resin, is provided under substantially rigid or semi-rigid substrate 58 to receive solidification energy transmitted through substrate 58. Solidification substrate 58 is generally rigid or semi-rigid and substantially permeable to the energy supplied by linear solidification device 62. In certain examples, it is preferred that the energy from linear solidification device 62 pass through solidification substrate 58 without a significant diminution in transmitted energy or a significant alteration of the energy spectrum transmitted to the solidification material 50 relative to the spectrum that is incident to the upper surface of solidification substrate 58. In the case where the energy from linear solidification device 62 is light (including non-visible light such as UV light), solidification substrate 58 is preferably substantially transparent and/or translucent to the wavelength(s) of light supplied by linear solidification device 62.

[0072] One example of a rigid or semi-rigid solidification substrate 58 is a translucent float glass. Another example is a translucent plastic. A variety of different float glasses and plastics may be used. Exemplary plastics that may be used include transparent and/or translucent acrylic plastics supplied by Evonik under the name Acrylite®. The term "translucent" is meant to indicate that substrate 58 is capable of transmitting the light wavelengths (including non-visible light such as UV light) necessary to solidify the solidifiable material and that the intensity of such wavelengths is not significantly altered as the light passes through substrate 58. In the case of photopolymer solidifiable materials, a photoinitiator is commonly provided to start the polymerization/cross-linking process. Photoinitiators will have an absorption spectrum based on their concentration in the photopolymer. That spectrum corresponds to the wavelengths that must pass through solidification substrate 58 and which must be absorbed by the photoinitiator to initiate solidification. In one example wherein solidification energy source in the linear solidification device 62 is a blue laser light diode, Irgacure 819 and Irgacure 714 photoinitiators may preferably be used.

[0073] Film 60 is preferably transparent and/or translucent and is a homopolymer or copolymer formed from ethylenically unsaturated, halogenated monomers. Fluoropolymers are

preferred. Examples of suitable materials for protective film 60 include polyvinylidene fluoride (PVDF), ethylenchlorotrifluoroethylene (ECTFE), ethylenetetrafluoroethylene (ETFE), polytetrafluoroethylene (PTFE), perfluoroalkoxy (PFA), and modified fluoroalkoxy (a copolymer of tetrafluoroethylene and perfluoromethylvinylether, also known as MFA). Examples of suitable film 60 materials include PVDF films sold under the Kynar® name by Arkema, ECTFE films sold under the Halar® name by SolvaySolexis, ETFE films sold under the Tefzel® name by DuPont, PFA films sold under the Teflon® -PFA name by DuPont, and MFA films sold under the name Nowofol. MFA and Teflon® films are preferred

[0074] The solidification substrate assembly 57 is attached to a work table 64 via a pair of hinges 74a and 74b (only hinge 74b is visible in FIGS. 1A-1E) which are both located on a first side 72a of the load frame 56 and spaced apart from one another along the y-axis. The hinges 74a and 74b are also attached to the work table 64 at a first side 65a of the work table 64. The hinges 74a and 74b define an axis of tilting or rotation for the solidification substrate assembly 57. Thus, during a tilting operation, the solidification substrate assembly 57 tilts about the axis defined by hinges 74a and 74b, which is parallel to the y-axis in the figures. In the example of FIGS. 4A-4E, solidification substrate assembly 57 also comprises linear solidification device 62.

[0075] The apparatus 40 includes a tilting actuator 66 that is operatively connected to the solidification substrate assembly 57. Actuator 66 has a housing 67 with a proximal end 73 and a shaft 68 with a distal end 70. The shaft 68 has a proximal end that is located in the housing 67 and which is not visible in the figures. In FIGS. 1A-1E the distal end 70 of actuator shaft 68 is connected to the left-side 72b of load frame 56 of the solidification substrate assembly 57. Right-side 72a of load frame 56 is spaced apart from left-side 72b along the x-axis. A bracket 76 is provided to connect the actuator 66 to the left-side 65b of the work table 64. Right-side 65a of work table 64 is spaced apart from left-hand side 65b along the x-axis. The position of actuator housing 67 is fixed relative to bracket 76 and the work table 64. However, the actuator shaft distal end 70 is movable relative to the work table 64 and the actuator housing 67 along the build (z) axis. The actuator 66 has an extended configuration (FIGS. 1C and 1D) and a retracted configuration (FIGS. 1A-B, and 1E). The length of actuator 66--as defined by the distance between the proximal actuator end 73 and the distal shaft end 70 along an axis defined by the

actuator shaft 68 length--is longer in the extended configuration than in the retracted configuration. The length axis of actuator shaft 68 is generally parallel to the build (z) axis and is substantially parallel to the build (z) axis when the solidification substrate assembly 57 is in a level configuration (FIGS. 1A-1B, and 1E). However, the actuator shaft 68 length axis will tilt relative to the build (z) axis during a solidification substrate assembly 57 tilting operation because the solidification substrate assembly 57 traverses a circular path when viewed along the y-axis during a tilting operation. The actuator shaft 68 will exhibit its maximum degree of tilt relative to the build (z) axis when the shaft distal end 70 reaches its fully extended position.

[0076] Suitable actuators 66 include pneumatic actuators and linear actuators that are electromechanical. One suitable electromechanical linear actuator is a 100 pound maximum lift linear actuator supplied by Ezzy Lift. The actuator has a two inch (2) stroke (i.e., the maximum displacement of the distal end 70 from a fully retracted to a fully extended configuration is two (2) inches (50.8 mm)). The Ezzy Lift actuator has a maximum actuator travel speed (which is equivalent to a peeling velocity tilting parameter described below) of 12.8 mm/sec.

[0077] The actuator 66 is adjustable from the retracted configuration to the extended configuration to tilt the solidification substrate assembly 57 about the tilting axis defined by hinges 74a and 74b (not shown). In the example of FIGS. 1A-1E, the actuator 66 is positioned with its shaft 68 underneath the load frame 56 along the build (z) axis. In FIG. 1A, the actuator 66 is in the retracted configuration in which distal shaft end 70 is in a first retracted position along the build (z) axis that is relatively closer to the build platform 46 and to the proximal actuator end 73 along the build (z) axis than when the actuator 66 is in the extended configuration (FIGS. 1C-1D) in which distal shaft end 70 is in a second extended position along the build (z) axis. Thus, in the example of FIGS. 1A-1E, the distal shaft end 70 has an extended position in which it is spaced apart farther from both build platform 46 and actuator 66 along the build (z) axis.

[0078] The actuator 66 is adjustable from the retracted configuration of FIGS. 1A-1B to the extended configuration of FIGS. 1C and 1D to cause the solidification substrate assembly 57 to tilt about the tilting axis in a direction away from the build platform 46. The tilting of the

solidification substrate assembly 57 away from build platform 46 may be used to carry out an object peeling operation as will be described further herein.

[0079] As FIGS. 1C and 1D indicate, the extension of the actuator shaft 68 from a retracted configuration to an extended configuration causes the solidification substrate assembly 57, including linear solidification device, the load frame 56, rigid or semi-rigid solidification substrate 58 and film 60, to tilt about the tilting axis defined by the hinges 74a (not shown) and 74b. However, as discussed further below with reference to the apparatus of FIG. 6, the actuator 66 may be configured differently so that the retraction of shaft 68 causes the solidification substrate assembly 57 to tilt away from the build platform 46. In that case, when the actuator shaft distal end 70 is in a first fully retracted position, the distal end 70 is spaced apart from the build platform 46 along the build (z) axis by a distance that is greater than the build (z) axis distance by which the distal shaft end 70 is spaced apart from the build platform 46 when actuator shaft distal end 70 is in a second fully extended position. In yet another alternative, and as discussed further below with respect to the example of FIGS. 10-13, the distal end 70 of the actuator 66 may be connected to a stationary surface such as work table 64 such that when the actuator 66 is in an extended configuration, the proximal end 73 moves away from the distal shaft end 70 and the build platform 46 and when the actuator 66 is a retracted configuration, the proximal end 73 moves toward the distal shaft end 70 and the build platform 46. In this configuration, the position of the proximal actuator end 73 relative to the tiltable solidification substrate assembly 57 remains fixed but is movable relative to the work table 64.

[0080] In certain known systems, following the solidification of a layer of solidifiable material, as depicted in FIG. 1B, the build platform 46 will descend by whatever distance is required to separate the exposed object surface 82 from the film 60 or rigid or semi-rigid solidification substrate 58 if no film is present. In such systems, the full peeling force is applied simultaneously across the entire exposed object surface 82 area of the object 78. The object 78 tends to become susceptible to breakage if the force per unit area of the exposed object surface 82 increases beyond a certain threshold. Therefore, in many known systems, the build platform 46 must be pulled away from the film 60 at a reduced speed to reduce the force per unit area and preserve the integrity of the object 78. In contrast, the peeling process carried out by the

apparatus of FIGS. 1A-1E and the other apparatuses described herein yields a dynamically varying force profile along the x-axis and reduces the force per unit area during peeling operations relative to processes in which an entire layer is separated by a vertical force. Also, in preferred implementations of the apparatus 40 of FIGS. 1A-1E, peeling may be completed before the build platform 46 moves. Thus, the peeling process is not dependent on the build platform 46 movement and does not limit the speed of build platform 46 movement.

[0081] FIG. 1C depicts the apparatus 40 with the solidification substrate assembly 57 in a peeled and tilted configuration in which the rigid or semi-rigid solidification substrate 58 and film 60 have fully separated from the exposed object surface 82. In FIG. 1C, actuator 66 is in an extended configuration. In some implementations, peeling operations may be carried out by extending the actuator shaft 68 by a fixed amount (the actuator peeling distance, which is shown as Δa in FIGS. 1A-1E) following the formation of each object layer. However, in other implementations, the actuator peeling distance may be varied based on the object data for the just-solidified layer. The location of the exposed object surface 82 along the x-axis for any given object layer will generally dictate the extent to which the actuator shaft 68 must be extended to fully peel the exposed object surface 82 from the film 60. Thus, in these other implementations, the actuator peeling distance Δa is adjusted for one or more layers of the three-dimensional object to effect the minimum degree of peeling required given the x-axis dimensions of the most recently formed object layer. Because of the hinged connection between the solidification substrate assembly's load frame 56 and the work table 64, the solidification substrate assembly 57 undergoes a circular motion (when viewed along the y-axis) during a peeling operation. As a result, those points of film 60 or substrate 58 which are in contact with locations on the exposed object surface 82 that are relatively farther (along the x-axis) from the tilting axis (defined by hinges 74a and 74b) will travel a greater distance during a tilting operation than will points of film 60 or substrate 58 that are in contact with locations on the exposed object surface 82 that are relatively closer (along the x-axis) to the tilting axis. Therefore, in certain implementations, the actuator peeling distance Δa is adjusted so that a portion on the exposed object surface 82 that is in contact with film 60 and which is closest (along the x-axis) to the tilting axis (i.e., closest to the hinges 74a and 74b) will travel during an object peeling operation from a starting location to

an ending location that defines a linear travel vector having a length equal to the minimum object peeling travel distance Δg. In such implementations, as the x-axis location of the portion of the exposed object surface 82 that is closest to the tilting axis varies, so will the actuator peeling distance Δa. This technique helps ensure that only the necessary amount of peeling is performed, which in turn reduces the time required to build three-dimensional parts. In FIG. 1C, the minimum object peeling distance Δg is shown as being a vertical spacing. However, in practice it is a vector with a variable direction which may or may not be parallel to the build (z) axis. Also, the actuator shaft 68 is shown as extending in a direction parallel to the build (z) axis. However, due to the hinged connection of the load frame 56 to the work table 64, the actuator distal end 70 will traverse a generally circular path during tilting operations, and thus, the shaft 68 may tilt away from the build (z) axis.

[0082] In the example of FIG. 1C, the exposed surface 51 of the solidifiable material 50 is beneath the fully retracted position of the actuator distal end 70 and the hinges 74a and 74b along the build (z) axis. In the figures, the difference between the vertical (z-axis) spacing between the actuator shaft distal end 70 and the exposed solidifiable material surface 51 on the one hand and the actuator shaft distal end 70 and hinges 74a and 74b on the one hand is identified as Δf. With this configuration, the rigid or semi-rigid solidification substrate 58 may be positioned beneath the open top of the solidifiable material container 44. In certain examples, the actuator peeling distance Δa may be calculated from the minimum object peeling travel distance Δg, using the following relationship:

(1) $$\Delta a = \frac{(Lt \times \Delta g)}{\sqrt{(Lp^2 + \Delta f^2)}}$$

wherein, Δa = actuator peeling distance (mm);

Lt = distance along the x-axis from actuator to hinges (mm);

Lp = shortest distance along the x-axis from exposed object surface to hinges (mm);

Δf = difference between (1) the z-axis distance between the actuator shaft distal end 70 and the exposed solidifiable material surface 51 and

(2) the z-axis distance between the actuator shaft distal end and hinges 74a and 74b (mm).

[0083] Sensors may be provided to indicate the completion of an object peeling operation. In one example, a limit switch may be provided which generates a signal when the actuator distal end 70 reaches its fully-extended, end of travel position along the build (z) axis. When fixed actuator peeling distances Δa are used carry out object peeling operations, the limit switch may be operatively connected to a controller and used by the controller to sequence subsequent operations following the completion of an object peeling operation.

[0084] Following the solidification of an object layer, the build platform 46 descends by a desired layer thickness Δz as shown in FIG. 1D. The build platform 46 may descend during the object peeling operation or following it. In preferred examples, the build platform 46 descends following the completion of the object peeling operation. The movement of the build platform 46 allows unsolidified solidifiable material 50 to flow into the region above the exposed object surface 82 and create a new exposed solidifiable material surface 51. In FIG. 1D, the exposed object surface 82 is spaced apart from the exposed solidifiable material surface 51 by the desired layer thickness Δz.

[0085] Prior to solidifying a new layer of solidifiable material 50, the solidification substrate assembly 57 is tilted into a level configuration by carrying out a leveling operation as shown in FIGS. 1D to 1E. To carry out the leveling operation, the distal end 70 of the actuator shaft 68 is retracted along the build (z) axis to its fully-retracted position, as shown in FIG. 1E. During the leveling operation, the rigid or semi-rigid solidification substrate 58 and film 60 apply a pressure in the negative build (z) axis direction against the solidifiable material 50 that is located in the region between the exposed object surface 82 and the film 60. This pressure has the effect of "squeezing" out material trapped in this region as shown by the curved arrows in FIG. 1E.

[0086] During the squeezing process, the solidifiable material experiences small localized waves and other transient hydrodynamic phenomena. Thus, in general, it is desirable to ensure that the squeezing operation is complete before the linear solidification device 62 begins solidifying the next layer to avoid distortions in the resulting three-dimensional object. One technique of ensuring that squeezing is complete is to wait until the expiration of a "leveling wait

time" after the solidification substrate assembly 57 is in the level configuration of FIG. 1E. In certain examples herein, leveling wait times of no more than about 60 seconds are preferred, and leveling wait times of no more than about 45 seconds, and no more than about 35 seconds, are more preferred and even more preferred respectively. At the same time, leveling wait times of at least about 2 seconds, at least about 5 seconds, and at least about 8 seconds are preferred, more preferred, and especially preferred, respectively. In one example, a leveling wait time of about 10 seconds is used.

[0087] As an alternative to using a leveling wait time, a pressure or force sensor may also be provided and used to determine when a squeezing operation is complete. The pressure sensor is preferably directly or indirectly indicative of the fluid pressure exerted by solidifiable material 50 against the film 60 and rigid or semi-rigid solidification substrate 58. During a squeezing operation, this pressure (which has a direction in the positive or upward build (z) axis direction) will decrease until squeezing is complete. An exaggerated schematic view of one possible pressure sensor configuration is depicted in FIG. 2. Pressure sensor 86 comprises a load cell attached to the left-hand side 65b of work table 64 so as to be spaced apart from the hinges 74a and 74b along the x-axis. A load bracket 84 is attached to the load frame 56 at the load frame left hand side 72b and overlaps with the pressure sensor 86 along the x-axis. The load bracket 84 applies a negative (downward) build (z) axis force against the pressure sensor 86. At equilibrium (i.e., when no squeezing is occurring) the weight of the solidification substrate assembly 57 will exert a non-zero reference force in the negative build (z) axis direction against the load cell which will be offset to some extent by the pressure exerted by the solidifiable material 50 against the film 60 and rigid or semi-rigid solidification substrate 58. Thus, the sensor 86 will produce a non-zero, equilibrium pressure reading when no squeezing is occurring.

[0088] With the pressure sensor 86 configured as shown, during a squeezing operation, the positive build (z) axis force applied by the solidifiable material 50 against the film 60 and rigid or semi-rigid solidification substrate 58 will provide a net force exerted against the pressure sensor 86 that is lower than the equilibrium force exerted against the sensor 86 when no squeezing is occurring. As squeezing continues, the positive build (z) axis force applied by the solidifiable material 50 will decrease, causing the pressure sensor 86 reading to increase toward

the equilibrium, non-zero reference pressure, which indicates that squeezing is complete. In addition to using the pressure value itself, the change in the pressure value with respect to time (*dP/dt*) may be used as an indication that squeezing is complete by comparing the change with a specified threshold change. In certain examples, the non-zero reference pressure (or reference value of *dP/dt*) is a tilting parameter and may be varied based on the particular solidifiable material 50 that is used. In general, more highly viscous solidifiable materials will exert a greater upward force against the film 60 and rigid or semi-rigid solidification substrate 58 at equilibrium, and for such materials are relatively higher non-zero reference pressure is selected as compared to lower viscosity materials.

[0089] In certain exemplary implementations, the actuator 66 applies a constant force against the solidification substrate assembly 57 during an object peeling operation. In other exemplary implementations, the actuator 66 applies a constant force against the solidification substrate assembly 57 during a leveling operation. In further exemplary implementations, the actuator 66 applies a constant force against the solidification substrate assembly 57 during both an object peeling operation and a leveling operation (albeit in opposite directions). In a preferred method, the same constant force is applied during an object peeling and a leveling operation (albeit in opposite directions), and the constant force (in the negative build (z) axis direction) remains after the solidification substrate assembly 57 is level, which stabilizes the assembly against the upward pressure of the solidifiable material 50.

[0090] In certain implementations of the apparatus 40 of FIGS. 1A-1E, it has been found that during the first several layers of an object solidification operation, it may not be possible to obtain sufficient solidifiable material 50 above the exposed object surface 82 to develop a new layer of solidifiable material 50 of the desired layer thickness Δz. Without wishing to be bound by any theory, it is believed that insufficient material is available above the upward facing surface 48 of the build platform 46 during the formation of the first several object layers to sufficiently cover the build platform 46 and the object 78 because of the close proximity of build platform 46 to the exposed surface 51 of the solidifiable material 50. Thus, in a "deep dipping" variation of the technique described in the preceding paragraph, during the formation of an initial set of object layers, the build platform 46 is dipped in the negative build (z) axis direction by an

amount greater than the desired layer thickness Δz and is subsequently elevated in the positive build (z) axis direction until the exposed object surface 82 is spaced apart from the exposed solidifiable material surface 51 by the desired layer thickness Δz. In preferred implementations of this variation, the deep dipping step is carried out during the formation of at least layer 2, more preferably during layers 2-3, still more preferably during layers 2-4, even more preferably during layers 2-5, still more preferably during layers 2-6, yet more preferably during layers 2-7, even more preferably during layers 2-8, and still more preferably during layers 2-9, and yet more preferably during layers 2-10. The deep dipping process is preferably carried out for no more than the first 30 layers, even more preferably no more than the first 20 layers, and still more preferably no more than the first 15 layers. When this deep dipping variation is used, the depth of the deep dipping is preferably at least about 2x, more preferably at least about 10x, more preferably at least about 40x, still more preferably at least about 50x, and yet more preferably at least about 100x the desired layer thickness Δz. At the same time, the depth of the deep dipping is preferably no more than about 400x, still more preferably no more than about 350x, even more preferably no more than about 300x, and even more preferably no more than about 200x the desired layer thickness Δz. Thus, in one example using a desired layer thickness Δz of 50 microns, the deep dipping depth ranges from 5-10mm, which is 100-200 times the layer thickness. In preferred examples, when deep dipping is used, solidification of the next object layer is deferred until the leveling wait time expires starting from the time when the solidification substrate assembly 57 is in the level configuration and the build platform 46 has been elevated so that the exposed object surface 82 is spaced apart from the solidification substrate assembly 57 by a distance along the build (z) axis equal to the desired layer thickness Δz.

[0091] In accordance with the deep dipping variation, there is preferably a waiting period between the completion of the deep dipping step and the elevation of the build platform 46 to a build (z) axis location at which the exposed object surface 82 is spaced apart from the exposed solidifiable material surface 51 by the desired layer thickness Δz. In preferred examples, the waiting period is preferably at least about one (1) second, more preferably at least about 1.5 seconds, and still more preferably at least about 2 seconds. At the same time, the waiting period

is preferably no more than about 10 seconds, still more preferably no more than about 8 seconds, and even more preferably no more than about 5 seconds. The deep dipping variation can be performed with or without tilting the solidification substrate assembly 57 or performing the leveling operation described above. However, if tilting is not used to perform an object peeling operation, the speed of descent of the build platform 46 in the negative build (z) axis direction must be reduced because object separation from the film 60 will occur during the descent and without tilting, the separation forces per unit area will generally be higher across the exposed object surface 82.

[0092] As indicated previously, the apparatus 40 of FIGS. 1A-1E preferably includes at least one controller that is operatively connected to the actuator 66. The at least one controller may comprise multiple controllers that are respectively used to control the actuator 66, the build platform motor (not shown), a linear solidification device motor (not shown) and internal components of the linear solidification device 62, such as a source of solidification energy and a linear scanning device. Alternatively, these functions may be provided in a single controller that includes the requisite inputs and outputs. A schematic illustration of a controller 184 that controls the linear solidification device 62, tilting actuator 66, and build platform 46 is shown in FIG. 3. Controller 184 includes a microprocessor 188 such as a central processing unit (CPU). Controller 184 also includes a non-transitory memory 186 that stores one or more programs (i.e., sets of computer executable instructions) which when executed by the processor 188 cause the controller 184 to perform various calculations and determinations and to generate various output signals from outputs 194 to connected devices.

[0093] Controller 184 includes a variety of inputs 192 for receiving sensor or other instrument signals used to carry out control functions. In the example of FIG. 3, controller 184 is connected to a pressure (or force) sensor 110, a build platform position indicator 208 (which may comprise a signal from a build platform motor that is indicative of the build platform 46 position along the build (z) axis), an actuator limit switch 210, and a solidification energy sensor 211. Solidification energy sensors are described in Applicant's co-pending U.S. Patent Application No. 13/534,638, including in FIGS. 5C and 5D and corresponding text including at paragraphs 102-110, 191-196, and 209-212, the contents of which are hereby incorporated by reference.

[0094] Controller 184 also includes a variety of outputs 194 for transmitting various actuation signals to different devices. In the example of FIG. 3, controller outputs 194 are connected (either directly or indirectly by way of intervening devices) to tilting actuator 66, build platform motor 200, linear solidification device motor 201, solidification energy source 204, and linear scanning device 207. Controller 184 also includes data ports 190 for receiving data from other devices. For example, controller 184 receives object data 198 that is representative of the three-dimensional object and which dictates the pattern of solidification energy projected through the rigid or semi-rigid solidification substrate 58 and film 60 and onto the exposed surface 51 of the solidifiable material 50. In certain examples, a computer (not shown) processes object data received in a first format and transmits it in a second format to data ports 190. For example, a host computer may receive CAD/CAM data or other object data and convert it into string data comprising a plurality of time values at which a solidification energy source is toggled on and off as linear solidification device 62 moves along the x-axis. Examples of string data are provided in Applicant's co-pending U.S. Patent Application No. 13/534,638, including in FIGS. 16(d), 16(f), and 16(g) and the corresponding text at paragraphs 167-170, and 176-181, the contents of which are hereby incorporated by reference.

[0095] Controller 184 is also operatively connected to a tilting parameter database 196. The tilting parameter database 196 comprises a non-transitory, computer readable medium having tilting parameter data stored on it. The tilting parameter database 196 may be provided as internal component in controller 184 or it may be a separate component from which controller 184 receives necessary tilting parameter data. In preferred examples, the tilting parameter database 196 includes names or other identifiers for a plurality of different solidifiable materials and a set of tilting parameters stored in association with each solidifiable material identifier. The set of tilting parameters for any given solidifiable material may comprise one or more tilting parameters. The tilting parameters may be selected from the group consisting of actuator peeling distance Δa, peeling velocity, leveling velocity, leveling wait time, pressure (or force) sensor reference pressure, pressure (or force) sensor reference change with respect to time (dP/dt), and minimum object peeling travel distance Δg, and any and all combinations thereof. In one exemplary implementation, controller 184 includes a program comprising a set of computer

executable instructions stored in memory 186 and when executed by processor 188, the computer executable instructions determine an actuator peeling distance Δa from a minimum object peeling travel distance Δg (FIG. 1C) and an x-axis location on the exposed object surface 82 that is closest to hinges 74a and 74b (i.e., the tilting axis) along the x-axis. The computer executable instructions then cause the controller 184 to generate an appropriate output signal (actuator activation signal) which is transmitted to the actuator 66 and which causes the actuator 66 to extend the distal shaft end 70 from the fully retracted position of FIGS. 1A and 1B to the desired actuator peeling distance Δa. In a further example, the computer executable instructions cause controller 184 to generate an appropriate actuator activation signal to retract the actuator distal shaft end 70 to the fully retracted position of FIG. 1E. Further examples of suitable computer executable instructions are described below with respect to FIGS. 7 and 8A-8B.

[0096] Referring to FIGS. 4A-4E, a detailed perspective view of an apparatus for making a three-dimensional object is described. The apparatus includes a solidification substrate assembly 57 and a work table 64. The apparatus also comprises a housing 42, build platform 46 (and shaft 52) and solidifiable material container 44 which are not shown for ease of illustration.

[0097] The solidification substrate assembly 57 includes a rigid or semi-rigid solidification substrate 58, a rigid or semi-rigid solidification substrate frame 88, load frame 120, film assembly 90, and linear solidification device 62. The work table 64 includes a central opening in which the solidification substrate assembly 57 is disposed. The solidification substrate assembly 57 is tiltable about a tilting axis that is defined by hinges 74a and 74b (FIGS. 4D) and which is parallel to the y-axis. Hinges 74a and 74b are attached to the load frame 120 and the work table 64 as shown in FIG. 4D. A stop 118 comprising a substantially flat member extending along the y-axis is provided to restrain the tilting of the solidification substrate assembly 57 in a direction toward the build platform (not shown). A wire conduit 106 is provided to connect at least one controller 184 to the linear solidification device 62.

[0098] An exemplary solidification substrate assembly 57 (without the linear solidification device 62 attached) is depicted in FIGS. 5A-5C. Rigid or semi-rigid solidification substrate 58 is attached to a solidification substrate frame 88 and projects beneath (along the build (z) axis) the sidewalls 132a (not shown) and 132b. Frame 88 is generally rigid structure which is preferably

metal. Solidification substrate frame 88 includes first and second sidewalls 132a and 132b which are spaced apart along the y-axis, and cross-members 94c and 94d spaced apart along the x-axis. The solidification substrate 58 has a bottom surface that projects beneath (along the z-axis) the lower surfaces of sidewalls 132a and 132b. The solidification substrate 58 is positioned inward of cross-members 94c and 94d along the x-axis and is attached to sidewalls 132a and 132b, which are spaced apart from one another along the y-axis.

[0099] Film assembly 90 includes a transparent and/or translucent film 60 and a frame assembly. The frame assembly comprises an inner frame 92 and an outer frame 91. The inner frame 92 includes an outwardly projecting lip 138. A peripheral portion of the film 60 is sandwiched between the lip 138 and the upper surface of the outer frame 91. The film 60 is preferably stretched tautly within the frames 92 and 91. In certain examples, film 60 may have a plurality of small grooves in its upward facing surface. In certain examples, the grooves minimize the likelihood of a vacuum forming between downward (build (z) axis) surface of the rigid or semi-rigid solidification substrate 58 and the upward (build (z) axis) facing surface of the film 60. However, such grooves are not necessary in many implementations.

[00100] Load frame 120 is a generally rectangular structure with side walls 104a and 104b spaced apart along the y-axis, and side walls 95c and 95d spaced apart along the x-axis. Actuator 66 includes actuator housing 67 and shaft 68. As best seen in FIGS. 4B-4C, shaft 68 has a distal end 70. Actuator housing 67 has a proximal end 73. Thus, the distance from the proximal housing end 73 to the shaft distal end 70 along an axis defined by the length of shaft 68 defines the length of the actuator 66. The actuator length is adjustable from a retracted configuration to an extended configuration. In the extended configuration, the distal end 70 of shaft 68 is spaced apart along the shaft 68 length axis and along the build (z) axis from the actuator housing proximal end 73 by a distance that is greater than the shaft 68 length axis and build (z) axis spacings between the distal end 70 and actuator proximal housing end 73 in the retracted configuration. In the extended configuration, the distal shaft end 70 is also spaced apart from a build platform (not shown) 46 by a distance along the build (z) axis that is greater than when the actuator 66 is in the retracted configuration. The length axis of actuator shaft 68 is generally parallel to the build (z) axis and is substantially parallel to the build (z) axis when the

solidification substrate assembly 57 is in a level configuration (FIG. 4A). However, the actuator shaft 68 length axis will tilt relative to the build (z) axis during a solidification substrate assembly tilt operation because the solidification substrate assembly 57 traverses a circular path when viewed along the y-axis during a tilting operation. The actuator shaft 68 will exhibit its maximum degree of tilt relative to the build (z) axis when the shaft distal end 70 reaches its fully extended position.

[00101] In the example of FIGS. 4A-4E, the position of the proximal end 73 of actuator housing 67 is fixed relative to the work table 64, and the position of the distal shaft end 70 relative to the work table 64 varies as the actuator 66 is adjusted from the retracted configuration to the extended configuration and vice-versa.

[00102] In FIG. 4A, the solidification substrate assembly 57 is in a level (untilted) configuration relative to work table 64. Actuator 66 is in a retracted configuration in which distal shaft end 70 is relatively closer (along the build (z) axis) to work table 64 and a build platform 46 (not shown) than when actuator 66 is in an extended configuration. In FIGS. 4B-4E, solidification substrate assembly 57 is in a tilted configuration relative to work table 64. When solidification substrate assembly 57 is in the tilted configuration, actuator 66 is in an extended configuration in which the distal shaft end 70 is relatively farther (along the build (z) axis) from work table 64 and the build platform 46 (not shown) than when the actuator 66 is in a retracted configuration.

[00103] The apparatus for making three-dimensional objects of FIGS. 4A-4E includes the solidification substrate assembly 57 of FIGS. 5A-5C. As with the example of FIGS. 1A and 1E, and as shown in FIG. 4A, when attached to work table 64, the film 60 and rigid or semi-rigid solidification substrate 58 are spaced apart from the work table 64 in the negative build (z) axis direction when the solidification substrate assembly 57 is in a level configuration. This arrangement allows the film 60 or substrate 58 (if film 60 is not provided) to be placed in contact with the exposed surface of the solidifiable material without subjecting the work table 64 or the load frame 120 to contact with the solidifiable material. Although not shown in FIGS. 4A-4E, film 60 includes an object contacting surface 61 that faces the closed bottom 45 of solidifiable material container 44 as illustrated in FIGS. 1A-1E. In addition, the build platform 46 of FIGS.

1A-1E would be provided, and the object build surface 48 would face the object contacting surface 61 of the film 60, the open top 47 of solidifiable material container 44 and the linear solidification device 62.

[00104] The solidification substrate frame 88 and the film assembly 90 are attachable to one another to define an assembled unit. Fasteners 130a-130d (FIGS. 5A-5B) are provided around the periphery of the outwardly extending lip 138 of the inner frame 92 and engage corresponding threaded holes 134a-134d in the bottom surfaces of the corners of the solidification substrate frame 88. In addition, the load frame 120 is attachable to the solidification substrate frame 88. Solidification substrate frame 88 includes knobs 96a-96b and 97a-97b. Knobs 96a-96b include threaded shafts 139a (not shown) and 139b (FIG. 5B) which engage threaded holes 137a (not shown) and 137b formed in the top surface of side 95c of load frame 120. Knobs 97a-97b include threaded shafts 133a (not shown) and 133b which engage corresponding holes 135a and 135b formed in the top surface of side 95d of load frame 120.

[00105] When solidification substrate frame 88 is attached to film assembly 90 and to load frame 120 as described above, the three components define an assembled solidification substrate assembly 57 as shown in FIG. 5C (the linear solidification device 62 is not shown in FIGS. 5A-5C). In the assembled condition of FIG. 5C, the film assembly frames 92 and 91 and film 60 are disposed beneath (along the z-axis) the load frame 120. The solidification substrate 58 is disposed beneath (along the z-axis) the load frame 120 and the outwardly extending lip 138 of the film assembly inner frame 92. The downward (along the z-axis) facing surface of solidification substrate 58 abuttingly engages the upward (along the z-axis) facing surface of film 60. Knobs 96a-96d and 97a-97b can be loosened to separate and lift the solidification substrate frame 88 and film assembly 90 as a unit from load frame 120, which is useful for maintenance operations such as replacing film 60 and/or the solidification substrate 58, if necessary.

[00106] Referring again to FIGS. 4A-4E, the depicted apparatus includes a linear solidification device motor 98 which is operable to traverse the linear solidification device 62 along the travel (x) axis. Linear solidification device 62 slidably engages linear slides 108a and 108b (not shown) which extend along the x-axis and are spaced apart from one another along the y-axis. The linear solidification device 62 is connected to linear bearings (not shown) that are

spaced apart from one another along the y-axis, each of which engages a respective one of the linear slides 108a and 108b (not shown). Linear solidification device motor 98 is connected to a rotating shaft 100 with a length along the y-axis. Pulleys 102a and 102b (not shown) are spaced apart from the motor shaft 100 along the x-axis and from one another along the y-axis. The Respective timing belts 101a and 101b (not shown) are spaced apart from one another along the y-axis and engage the motor shaft 100 on one end and one of the two pulleys 102a and 102b on the other end. The pulleys 102a and 102b and timing belts are located in housings 115a and 115b, respectively.

[00107] The linear solidification device 62 is connected to each timing belt 101a and 101b. Thus, operation of motor 98 causes the shaft 100 to rotate about its longitudinal axis, which in turn causes the timing belts 101a and 101b to circulate. The circulation of the timing belts 101a and 101b traverses the linear solidification device 62 along the x-axis with its attached linear bearings slidably engaging the linear slides 108a and 108b (not shown). Suitable configurations of a linear solidification device motor, pulleys, timing belts, and linear slides are provided in FIGS. 3-4 and 7-8 of Applicant's co-pending U.S. Patent Application No. 13/534,638 and the corresponding text at paragraphs 84-85 and 124-125, the contents of which are hereby incorporated by reference.

[00108] As mentioned previously, load frame 120 includes first and second side walls 104a and 104b which are spaced apart along the y-axis. Load frame 120 also includes third and fourth side walls 95c and 95d which are spaced apart along the x-axis. Hinges 74a and 74b are attached to side 95d of the load frame 120, as shown in FIG. 4D. Load frame 120 also includes a latch 114 (not shown in FIGS. 5A-5C) that is used to releasably secure the load frame 120 to the distal end 70 of the tilting actuator shaft 68. Latch 114 includes a knob 116 attached to a sliding latch shaft 122. A user can grip the knob 116 and slide it within y-axis groove 126 to slide the latch shaft 122 along the y-axis direction. A first end of the shaft 122 can be selectively inserted into and retracted from an opening 124 in the distal end 70 of the tilting actuator shaft 68. The engagement of the latch shaft 122 and the actuator shaft distal end opening 124 connects the load frame 120 to the actuator shaft 68. Once the latch shaft 122 is engaged in the opening 124, a user can rotate the knob 116 in the x-z plane within vertical groove 128. Vertical groove 128 is

dimensioned to substantially prevent the latch shaft 122 from moving along the y-axis. Thus, the rotation of the knob 116 locks the load frame 120 and the actuator shaft 68 into engagement with one another, thereby operatively connecting the actuator 66 to the solidification substrate assembly 57 so that movement of the actuator shaft 68 causes the solidification substrate assembly 57 to tilt about the tilting axis defined by hinges 74a and 74b. As best seen in FIG. 4C, the engagement between the latch shaft 122 and the opening 124 in the distal end 70 of the actuator shaft 68 allows the distal shaft end 70 to rotate relative to the latch 114 as the solidification substrate assembly 57 is tilted. The rotation allows for rotation of the solidification substrate assembly 57 about hinges 74a and 74b such that the distal end 70 of the actuator shaft 68 will traverse a circular path (when viewed along the y-axis) during tilting operations.

[00109] As discussed previously with respect to the example of FIGS. 1A-1E, in certain implementations a pressure (or force) sensor may be provided and used to determine when a squeezing operation is complete (i.e., to determine when the squeezing of solidifiable material between an exposed object surface and the film 60/substrate 58 is complete). In FIGS. 4A, 4B, and 4E, a pressure sensor 110 in the form of a load cell is attached to work table 64 on work table side 65b. A load bracket 112 is disposed on the load frame 120 and engages the load cell 110 when the solidification substrate assembly 57 is in a level configuration (FIG. 4A) and disengages from the load cell 110 when the solidification substrate assembly 57 is in a tilted configuration. An adjustment screw 113 is provided, and its length of extension from load bracket 112 can be adjusted to engage the load bracket 112 and the load cell 110. The length of extension of screw 113 from load bracket 112 can be adjusted to calibrate the orientation of the solidification substrate assembly 57 relative to the x-y plane when the solidification substrate assembly 57 is in the level or "home" position. In preferred examples, the length of extension of screw 113 from load bracket 112 is adjusted so that the rigid or semi-rigid solidification substrate 58 and/or film 60 are substantially or completely parallel to the x-y plane when the solidification substrate assembly is in the level (home) position.

[00110] Pressure (or force) sensor 110 is configured to operate in the same manner described previously with respect to pressure (or force) sensor 86 of FIG. 2. In examples wherein pressure (or force) sensor 110 is provided, it is preferably connected to controller 184 so that the pressure

(or force) sensor 110 signal can be used by computer executable instructions executed by processor 188 to determine when a leveling operation is complete and an object solidification operation for a new layer of solidifiable material can begin.

[00111] The actuator 66 depicted in FIGS. 4A-4E is an electromechanical linear actuator that includes a motor 69 connected to shaft 68. Controller 184 is preferably connected to motor 69 or to a source of current supplied to motor 69 to operatively connect the controller 184 and the actuator 66. In certain examples, during peeling and/or leveling operations, the controller 184 generates an actuator activation signal having a value that corresponds to a desired tilting parameter. For example, in one implementation, the controller 184 is connected to a source of variable current which is used to energize motor 69, and the current can be modulated to obtain a desired peeling and/or leveling velocity. As with the example of FIGS. 1A-1E, one or more limit switches may be provided to generate a signal when the actuator shaft distal end 70 has reached a fully extended and/or fully retracted position. The limit switch signal(s) may then be used by the computer executable instructions resident in the controller memory 186 to carry out subsequent operations. In one example, the computer executable instructions cause controller 184 to begin transmitting a build platform activation signal to a build platform motor (not shown) to move the build platform 46 down by one layer thickness Δz along the build (z) axis once the limit switch generates a signal indicating that the actuator shaft 68 is fully extended (or at some specified time after the limit switch generates the signal). In another example or at the same time, the computer executable instructions cause the controller 184 to generate an actuator activation signal that tilts the rigid or semi-rigid solidification substrate 58 and film 60 about the tilting axis and toward the build platform 46 when the limit switch generates a signal indicating that the actuator shaft 68 is fully extended (or at some specified time after the limit switch generates the signal). In certain exemplary implementations, the actuator 66 applies a constant force against the solidification substrate assembly 57 during an object peeling operation. In other exemplary implementations, the actuator 66 applies a constant force against the solidification substrate assembly 57 during a leveling operation. In further exemplary implementations, the actuator 66 applies a constant force against the solidification substrate assembly 57 during both an object peeling operation and a leveling operation (albeit in opposite directions). In a preferred method,

the same constant force is applied to the solidification substrate assembly 57 during an object peeling and a leveling operation (in opposite directions) and the constant force (in the negative build (z) axis direction) used in the leveling operation remains after the solidification substrate assembly 57 is level, which stabilizes the assembly 57 against the upward pressure of the solidifiable material. In one example, a constant force of 80 psi is applied to the solidification substrate assembly 57 during both an object peeling and a leveling operation.

[00112] In general, during leveling operations it is preferable to use a leveling wait time that ensures the squeezing of solidifiable material between the exposed object surface 82 and the solidification substrate assembly 57 is substantially or entirely complete before beginning a solidification operation. However, in some cases, when the solidification substrate assembly 57 is in the level configuration (FIG. 1E) and solidification of the next layer of solidifiable material has not yet begun, it may be desirable to operate the actuator 66 to apply a force that opposes the force of the solidifiable material 50 against the solidification substrate assembly. This force may be referred to as the "level configuration force". Applying a level configuration force to the solidification substrate assembly 57 better ensures that if there are any fluid disturbances or other hydrodynamic phenomena, they do not move the solidification substrate assembly 57. In the case of actuator 66 in FIGS. 1A-1E and 4A-4E, the opposing actuator force is applied in the downward build (z) axis direction to oppose the force applied by the solidifiable material 50 in the upward build (z) axis direction (see FIG. 2). For actuator 66, the opposing force is applied by applying a downward build (z) axis force to actuator shaft 68 because it is connected to the load frame 56 of solidification substrate assembly 57.

[00113] When actuator 66 is an electromechanical actuator, repeatedly applying an opposing level configuration force to the solidification substrate assembly 57 can shorten the life of the motor 69 used to operate the actuator 66. Thus, in certain examples, the motor 69 is operated in a modified mode when the solidification substrate assembly 57 is in a level configuration and solidification of the next layer of solidifiable material 50 has not yet begun. In one example, during at least a portion of the time in which the solidification substrate assembly 57 is in a level configuration and solidification of the next object layer has not yet begun, the motor 69 is operated at less than 100 percent of the load applied during a leveling operation so that the level

configuration force is correspondingly reduced relative to the force applied as the solidification substrate assembly 57 is being tilted during a leveling operation (the "leveling operation force") prior to reaching a level configuration. In certain examples, the level configuration force is no more than about 90 percent, preferably no more than about 80 percent, and still more preferably no more than about 70 percent of the leveling operation force, and the motor 69 electrical load is correspondingly no more than about 90 percent, preferably no more than about 80 percent, and still more preferably no more than about 70 percent of the electrical load during a leveling operation. When a solidification operation begins by traversing the linear solidification device along the travel (x) axis and supplying solidification energy to the solidifiable material along the scanning (y) axis, the electrical load applied to motor 69 is restored to 100 percent of the load applied during a leveling operation and remains there until solidification of the current layer is complete.

[00114] In another example, when the solidification substrate assembly 57 is in a level configuration and a solidification operation has not yet begun, the motor 69 electrical load is pulsed with alternating pulses of different magnitudes. In one implementation, the alternating pulses include 100 percent of the load used during a leveling operation and a value less than that load, which is preferably not more than about 70 percent, more preferably not more than about 60 percent, and still more preferably not more than about 50 percent of the load used during a leveling operation. When a solidification operation begins by traversing the linear solidification device along the travel (x) axis and supplying solidification energy to the solidifiable material along the scanning (y) axis, the electrical load applied to motor 69 is restored to 100 percent of the load applied during a leveling operation and remains there until solidification of the current layer is complete.

[00115] Referring to FIGS. 14A and 14B, examples of methods of operating the motor 69 to apply a leveling operation force and a level configuration force are depicted. In each of the figures the letter "A" refers to a leveling operation during which the solidification substrate assembly 57 is tilted toward the level configuration. In FIGS. 1A-1E, the actuator 66 retracts from an extended position to a retracted position during the leveling operation, and thus applies a downward force along the build (z) axis to the solidification substrate assembly 57. The letter

"B" refers to a level solidification substrate assembly 57 configuration in which a level configuration force is applied by the actuator 66 to the solidification substrate assembly 57 but during which solidification of the solidifiable material 50 is not taking place. The letter "C" refers to a level solidification substrate assembly 57 configuration during which solidification has begun. Thus, in phase C the linear solidification device 62 travels along the travel (x) axis while selectively supplying solidification energy along the scanning (y) axis in a pattern that corresponds to a portion of the three-dimensional object being built.

[00116] In FIG. 14A, during phase B the motor 69 electrical load drops to a value that is less than 100 percent of the electrical load during phases A and C. However, the load remains substantially constant or constant during the entirety of phase B. In FIG. 14B, during phase B the motor 69 electrical load is pulsed in alternating pulses of 100% and 50% of the loads during phases A and C. In the methods illustrated by FIGS. 14A and 14B, during phase B there is at least some period of time during which the motor 69 load and the level configuration force are less than the motor 69 load and the force during a leveling operation (phase A) and a solidification operation (phase C). The motor 69 load and force during phase B may be constant, variable, pulsed, or irregular. However, at some point during phase B the motor 69 load and actuator 66 force are less than during phases A and C.

[00117] Referring to FIG. 6, another exemplary solidification substrate assembly 57 and work table 64 apparatus for forming a three-dimensional object from a solidifiable material is depicted. The apparatus is similar to that of FIGS. 4A-4E in several respects and like numerals refer to like parts. However, in the apparatus of FIG. 6 the actuator is a pneumatic actuator 166 that is attached in the opposite vertical (build axis) orientation of actuator 66. Pneumatic actuator 166 comprises a hydraulic fluid cylinder 169 and a shaft 168. Cylinder 169 includes a proximal end 173 of the pneumatic actuator 166, and shaft 168 includes a distal end 170 which is the distal end of the actuator 166. Thus, actuator 166 has a length defined by a distance along the shaft 168 length axis between the cylinder proximal end 173 and the shaft distal end 170. The length axis of actuator shaft 168 is generally parallel to the build (z) axis and is substantially parallel to the build (z) axis when the solidification substrate assembly 57 is in a level configuration shown in FIG. 6. However, the actuator shaft 168 length axis will tilt during a solidification substrate

assembly tilt operation because the solidification substrate assembly 57 traverses a circular path when viewed along the y-axis during a tilting operation. The actuator shaft 168 will exhibit its maximum degree of tilt relative to the build (z) axis when the shaft distal end 170 reaches its fully retracted position. The actuator length is adjustable from a retractable configuration to an extended configuration and vice-versa. When the actuator 166 is in the extended configuration, the actuator distal end 170 is spaced apart (along the shaft 168 length axis and the build (z) axis) from the cylinder proximal end 173 by a distance that is greater than the distance by which the actuator distal end 170 is spaced apart (along the shaft 168 length axis and the build (z) axis) from the cylinder proximal end 173 when the actuator 166 is in the retracted configuration. When actuator 166 is in the extended configuration, the actual distal end 170 is spaced apart along the build (z) axis from the build platform (not shown in FIG. 6, but shown in FIGS. 1A-1E) by a distance that is shorter than when the actuator 166 is in the retracted configuration.

[00118] The shaft 168 is partially and selectively retractable into and extendable from the interior of hydraulic fluid cylinder 169. Distal end 170 of shaft 168 is connected to an upper surface of load frame 120 via bracket 172. Proximal end 173 of the cylinder 169 is attached to a stationary mounting platform 140 via bracket 174. The stationary mounting platform 140 is connected to a housing (not shown). The connection between the distal end 170 of the shaft and the bracket 172 allows the distal end 170 to rotate in the x-z plane relative to the bracket 172 to facilitate tilting about the tilting axis defined by the hinges 74a and 74b (not visible in FIG. 6). As a result, distal shaft end 170 will traverse a circular path when viewed along the y-axis during solidification substrate assembly 57 tilting operations.

[00119] The position of the proximal end 173 of actuator 166 remains fixed with respect to stationary mounting platform 140. However, the distal end 170 of actuator shaft 168 is movable relative to the stationary mounting platform 140 and relative to build platform 46 (not shown). Thus, extending the actuator 166 from the retracted configuration to the extended configuration causes the solidification substrate assembly 57 (including the solidification substrate frame 88, solidification substrate 58, film assembly 90, and linear solidification device 62) to tilt about the tilting axis defined by hinges 74a and 74b (not visible in FIG. 6) in a direction toward the build platform (not shown but would be positioned underneath the film assembly 90 along the build (z)

axis) and away from stationary mounting platform 140 until load frame bracket 112a reaches abutting engagement with load cell 110. Solidifiable material located between the film 60 of film assembly 90 and the build platform (not shown) would exert an upward force (and pressure) along the build (z) axis that will diminish as solidifiable material is squeezed out of the space between the exposed object surface 82 (FIGS. 1A-1E) and object contacting surface 61 of film 60. As explained below, the signal generated by pressure (or force) sensor 110 can be used by controller 184 to determine when to supply solidification energy from the linear solidification device 62 to the solidifiable material. In one example, the pressure (or force) sensor 110 provides a pressure signal to the controller 184 via inputs 192 and once the pressure signal reaches a predetermined value (or within a fixed or variable time thereafter), solidification may begin. In another example, the controller 184 may determine the rate of change of the pressure signal (*dP/dt*), and solidification may begin once the rate of change of the pressure signal reaches a predetermined value (or within a fixed or variable time thereafter).

[00120] Hydraulic fluid cylinder 169 comprises an interior volume of hydraulic fluid that engages a piston (not shown) on one end of shaft 168 that is contained in the interior of the cylinder 169. As hydraulic fluid is supplied to the cylinder 169, the piston is displaced along the length of the cylinder 169 in the negative build (z) axis direction, causing the distal end 170 of the shaft 168 to extend in the negative build (z) axis direction. Conversely, as hydraulic fluid is withdrawn from cylinder 169, the piston moves in the positive build (z) axis direction, causing the distal end 170 of the shaft 168 to retract in the positive build (z) axis direction. Thus, in the apparatus of FIG. 6, when the distal end 170 of the actuator shaft 168 is in its fully extended position along the build (z) axis, the solidification substrate assembly 57 is in a level configuration, with the rigid or semi-rigid solidification substrate 58 and film 60 substantially parallel to the upward facing surface 48 of the build platform 46 (FIGS. 1A-1E). During an object peeling operation, hydraulic fluid is withdrawn from the cylinder 169, causing the distal end 170 of the actuator shaft 168 to retract from an extended position to a retracted position. A vertical stop 171 comprising an annular ring is tightly engaged with the shaft 168 and limits the retraction of the shaft 168 within the interior of hydraulic fluid cylinder 169. The engagement of the piston (not shown) with the distal interior wall (not shown) of the cylinder 169 limits the

extension of the shaft 168. A source of hydraulic fluid is also provided but is not shown in FIG. 6. Controller 184 (FIG. 3) is operatively connected to the source of hydraulic fluid to selectively supply and withdraw hydraulic fluid from the cylinder 169. In certain examples, controller 184 is operatively connected to a hydraulic fluid pump and generates an actuator activation signal having a value that corresponds to the flow rate of hydraulic fluid into the cylinder, which in turn corresponds to the speed of movement of the actuator shaft 168. When the shaft 168 is retracting into the cylinder 169, the speed of movement of the actuator shaft 168 is the peeling velocity. When the shaft 168 is extending from the cylinder 169, the speed of movement of the actuator shaft 168 is the leveling velocity.

[00121] In certain exemplary implementations, the actuator 166 applies a constant force against the solidification substrate assembly 57 during an object peeling operation. In other exemplary implementations, the actuator 166 applies a constant force against the solidification substrate assembly 57 during a leveling operation. In further exemplary implementations, the actuator 166 applies a constant force against the solidification substrate assembly 57 during both an object peeling operation and a leveling operation (albeit in opposite directions). In a preferred method, the same constant force is applied during an object peeling and a leveling operation, and the constant force (in the negative build (z) axis direction) applied during the leveling operation remains after the solidification substrate assembly 57 is level (the level configuration force), which stabilizes the assembly against the upward pressure of the solidifiable material 50.

[00122] In the illustrated example of FIG. 6, the level configuration force is applied by extending the actuator 166 from a retracted configuration to an extended configuration, which applies a downward build (z) axis force to solidification substrate assembly 57 to oppose the upward build (z) axis force of the solidifiable material (FIG. 2). For actuator 166 the opposing downward build (z) force is applied by applying a downward build (z) axis force to actuator shaft 168 because it is connected to the load frame 56 of the solidification substrate assembly 57.

[00123] Actuator 166 is hydraulic but could also be motor-driven. If a motor-driven actuator 166 were used, level configuration forces may be applied as described previously with respect to the apparatuses of FIGS. 1A-1E and 4A-4E and as further illustrated in FIGS. 14A-B.

[00124] In the apparatus of FIG. 6, a second hydraulic actuator 176 is provided. The second hydraulic actuator 176 is used to tilt the entire solidification substrate assembly 57 out of the central opening in the work table 64 and into a substantially upright condition. The second hydraulic actuator 176 is not used for peeling or leveling operations. A proximal end of the second hydraulic actuator 176 is connected to a second stationary mounting platform 142 via bracket 182. A distal end of the second hydraulic actuator shaft 178 is connected to the load frame 120 via bracket 180.

[00125] Referring to FIG. 7, a first method of making a three-dimensional object using a tilting solidification substrate assembly will now be described. Apparatuses useful for carrying out the method include, but are not limited, to the apparatuses of FIGS. 1A-6, 10-13, and 16A-16F.

[00126] The steps described in FIG. 7 may be embodied as a set of computer executable instructions stored in memory 186 of controller 184. In step 1010, object data which is representative of the three-dimensional object is read. The object data may be provided for the entire object at once or just for one or more layers of the object. A layer index k is initialized in step 1012 and incremented by one in step 1014. Based on the object data for the current layer, a determination is made as to the farthest x-axis coordinate for the layer in step 1016. The term "farthest" indicates that the location is the farthest from the actuator 66, 166 and closest to the hinges 74a and 74b in a direction along the x-axis. The coordinate x_{max} will correspond to the last x-axis position of the linear solidification device 62 at which solidification will occur for a given layer. For example, in the apparatuses of FIGS. 1-6, the linear solidification device 62 will travel in two directions along the x-axis. However, object solidification operations will only be carried out while the linear solidification device 62 travels in one of the x-axis two directions. When viewing the apparatus of FIGS. 1A-1E along the y-axis and in the depicted orientation, solidification operations are carried out when the linear solidification device 62 travels away from actuator 66 and towards the tilting axis defined by the hinges 74a and 74b. The linear solidification device 62 also travels back in the opposite direction along the x-axis, but no object solidification operations are carried out. Similarly, in the apparatuses of FIGS. 4A-6, object solidification operations are performed when the linear solidification device 62 travels along the

x-axis in a direction away from the actuator 66, 166 and toward the hinges 74a and 74b. However, solidification operations are not carried out when the linear solidification device 62 moves along the x-axis in a direction toward the actuator 66, 166 and away from the hinges 74a and 74b. In apparatuses that use spatial light modulation techniques such as digital light projectors, all locations on the exposed solidifiable material surface 51 which are to be solidified will be solidified simultaneously. Thus, x_{max} in FIGS 1A-6 will be the x-axis location closest to the hinges 74a and 74b and farthest from the actuator 66, 166 but because a spatial light modulation technique is used, there will be no moving solidification energy source having a position along the x-axis that defines x_{max}. If a two-dimensional laser drawing technique is used, the galvanometer mirrors will move in a pattern that defines the exposure pattern on the solidifiable material. For each layer, the pattern will have a value of x_{max}.

[00127] In step 1018 the exposed surface 51 (FIGS. 1A-1E) of the solidifiable material 50 is exposed to solidification energy. In the case of a spatial light modulated system, the exposed surface 51 will receive one or more two-dimensional energy patterns projected in the x-y plane as static images. In the case of a linear solidification device 62, the device 62 will travel along the x-axis and supply linear patterns of solidification energy with lengths along the y-axis in step 1018. The expression *P(x,y)* in step 1018 refers to the set of all x, y coordinates at which solidification occurs. Since those x, y values will vary with the layer, step 1018 indicates that *P(x, y)* is a function of the layer, i.e., *P(k)*.

[00128] In step 1020 a determination is made as to whether each y-axis location at the farthest x-axis location x_{max} has been solidified. In the case of spatial light modulated systems, this step will be unnecessary because each y-axis location at a given x-axis location will simultaneously receive solidification energy from the solidification energy source. However, in the case of linear solidification devices 62 that use linear scanning devices, solidification energy will be progressively supplied along the y-axis at a given x-axis location. Thus, the layer solidification will not be complete until each y-axis location where solidification will occur at the farthest x-axis location x_{max} has been solidified. If all such y-axis locations have not been solidified, control returns to step 1018 and solidification along the y-axis continues. Otherwise, solidification of the layer is complete and control transfers to step 1022.

[00129] Referring to FIG. 3, if controller 184 is provided, in step 1018 the controller 184 will provide a signal to operate the linear solidification device motor 98 to move linear solidification device 62 along the x-axis. As the linear solidification device 62 moves along the x-axis, the controller 184 will also provide appropriate signals to the solidification energy source 204 (e.g., a laser diode, such as laser diode 90 shown and described in FIGS. 3, 4, and 5A-5D of Applicant's co-pending U.S. Patent Application No. 13/534,638, filed on June 27, 2012 and the corresponding text, including at paragraphs 60-79 and 86-104) and a linear scanning device (e.g., motor that rotates a polygonal mirror, such as motor 118 which rotates polygonal mirror 92 in U.S. Patent Application No. 13/534,638) to carry out a layer solidification operation. Even with linear solidification device 62, step 1020 will not be necessary if peeling is deferred until the linear solidification device 62 completes its traversal of the entire build envelope (the x-y area of the resin that is subject to solidification) in the x-axis direction. However, step 1020 beneficially makes use of the dynamic assessment of object layer data to initiate peeling operations as soon as possible, which further reduces overall object build times.

[00130] In step 1022 at least one controller (e.g., controller 184 of FIG. 3) generates a first actuator activation signal to carry out a peeling operation by tilting the solidification substrate assembly 57 away from the build platform 46. In the case of actuator 66, the first actuator activation signal will cause the shaft 68 to extend from a fully retracted configuration to a fully extended configuration (unless variable actuator peeling distances are used, in which case the actuator shaft 68 would not necessarily extend to a fully extended position). In the case of actuator 166, the first actuator activation signal will cause the shaft 168 to retract from a fully extended configuration to a retracted configuration. In certain preferred implementations, step 1022 begins about one (1) second after the completion of a layer solidification operation in step 1018. In certain exemplary implementations, step 1022 is carried out using a peeling velocity of at least about 0.1, preferably at least about 0.2, and more preferably at least about 0.3 mm/seconds. At the same time, the peeling velocity is no more than about one (1) mm/second, more preferably no more than about 0.8 mm/second and still more preferably no more than about 0.7 mm/second. In one exemplary implementation, a peeling velocity of 0.5 mm/seconds is used.

As mentioned previously, the peeling velocity refers to the linear speed of travel of the distal end 70, 170 of the actuator shaft 68, 168 during a peeling operation.

[00131] A determination is made in step 1024 as to whether peeling is complete. If it is, control transfers to step 1026. Otherwise, control returns to step 1024 and peeling continues. In certain implementations, a constant actuator peeling distance Δa is used and a limit switch is provided to determine when the actuator shaft 68, 168 has reached the actuator peeling distance Δa. In other implementations, however, a variable actuator peeling distance Δg (FIG. 1C) may be calculated from object data and a desired minimum object peeling travel distance. In such cases, other techniques may be used to determine whether the calculated actuator peeling distance has been reached. In the case of hydraulic actuators, the total amount of hydraulic fluid that is supplied to or withdrawn from the cylinder 169 may be used indicate the distance of travel of the distal shaft end 70, 170. In the case of electromechanical actuators, motor parameters such as activation time or both activation time and current may be used to indicate the distance of travel of distal shaft end 70, 170.

[00132] In step 1026 the method determines if the final layer has been solidified, as indicated by the value of the current layer index k relative to the index of the last object layer k_{max}. If the last layer has been reached, the method ends. Otherwise, control transfers to step 1028 to begin the process of providing a new layer of solidifiable material.

[00133] In step 1028 the build platform 46 (FIGS. 1A-1E) is moved downward in the negative build (z) axis direction by one layer thickness Δz. In certain exemplary implementations herein, the layer thickness Δz is preferably no more than about 250 microns, still more preferably no more than about 200 microns, more preferably no more than about 150 microns, even more preferably no more than about 100 microns, and yet more preferably no more than about 60 microns. At the same time, the layer thickness Δz is preferably no less than about 10 microns, still more preferably no less than about 20 microns, even more preferably no less than about 30 microns, and yet more preferably no more than about 40 microns. In one example, a layer thickness Δz of about 50 microns is used. Step 1028 may be carried out during all or part of steps 1022-1026. However, in preferred examples, step 1028 is carried out after step 1024 indicates that peeling is complete. In many known processes, the build platform 46 must be

moved downward by greater than the desired layer thickness to separate the exposed object surface 82 from the film 60. However, the method of FIG. 7 avoids the need for manipulating the build platform 46 to effect peeling. In the known processes, the position of the build platform 46 when solidifying the last object layer is necessarily limited by the requirement to drop the platform 46 by an amount greater than the desired layer thickness. As a result, solidifiable material is trapped in the container 44 at a height equal to the distance beneath the layer thickness which the platform 46 must be dropped to effect object separation from the film 60. This trapped solidifiable material cannot be used to form the object 78. Among other advantages, the method of FIG. 7 eliminates this trapping and maximizes the amount of solidifiable material available for forming three-dimensional object 78.

[00134] In certain implementations, controller 184 receives a signal from the build platform motor indicating when the platform 46 has stopped in its descent. In such implementations, the leveling operation of step 1030 is carried out either when the signal is received or within a fixed time thereafter. In such embodiments, the fixed time is preferably selected to ensure that the descent of the build platform for the next layer solidification operation is complete. In other implementations, the leveling operation is carried out within a fixed time after an object peeling operation is complete.

[00135] Following the completion of step 1028, a leveling operation is commenced. In step 1030 the controller (e.g., controller 184) will generate a second actuator activation signal to tilt the solidification substrate assembly toward the build platform until the actuator shaft 68, 168 reaches its "home" or "level" position. In the case of actuator 66, the controller's issuance of the second actuator activation signal will cause the distal end 70 of actuator shaft 68 to retract from a fully extended to a fully retracted position (unless variable actuator peeling distances Δa are used in which case the actuator shaft 68 would not necessarily start from a fully extended position). As described previously with respect to FIG. 1E, once the leveling object is complete, solidifiable material may continue to "squeeze out" of the space between the exposed object surface 82 and the film 60/rigid or semi-rigid solidification substrate 58. It is preferable to defer the beginning of another layer solidification operation until the squeezing operation is complete. In step 1032 a determination is made as to whether a pressure sensor is present for use in

determining when squeezing is complete. Suitable pressure sensors include sensors 86 (FIGS. 1A-1E) and 110 (FIGS. 4A, 4B, 4E, and 6) described previously. If a pressure sensor is present, in step 1034 the method waits until the pressure (or rate of change of pressure, *dP/dt*) indicated by the sensor 86, 110 reaches a desired set point (step 1036). As explained previously, the set point may comprise a value selected based on the nature of the solidifiable material. Once the sensed pressure reaches the set point in step 1036 (or once the change in pressure with respect to time *dP/dt* reaches a certain threshold), control transfers to step 1014 to increment the layer index and begin solidifying another layer.

[00136] In certain exemplary implementations, step 1028 is carried out using a leveling velocity of at least about 0.1, preferably at least about 0.2, and more preferably at least about 0.3 mm/seconds. At the same time, the leveling velocity is no more than about one (1) mm/second, more preferably no more than about 0.8 mm/second and still more preferably no more than about 0.7 mm/second. In one exemplary implementation, a leveling velocity of 0.5 mm/seconds is used. As mentioned previously, in the apparatuses of FIGS. 1A-1E, 4A-4E, 6, and 16A-16F) the leveling velocity is the linear speed of travel of the distal end 70, 170 of the actuator shaft 68, 168 during a leveling (squeezing) operation. In certain examples, multiple leveling velocities may be used. In one implementation, higher leveling velocities are used at the beginning of leveling, and lower leveling velocities are used toward the end of leveling. The higher velocities are used while the solidification substrate frame 88, load frame 120, and film assembly 90 tilt toward the build platform 46 before appreciable material squeezing beings and lower velocities are used after squeezing begins. The beginning of appreciable squeezing may be determined using pressure sensor 110, when the solidification substrate assembly 57 reaches a particular tilt angle relative to work table 64, or after a particular initial leveling period has expired.

[00137] If no pressure sensor is present in step 1032 (see the apparatus of FIG. 4E), the method waits until a leveling wait time expires (step 1034). Once the leveling wait time expires, control transfers to step 1014 to increment the layer index *k* and begin the solidification of another layer. The leveling wait time and the pressure sensor setpoint (or *dP/dt* setpoint) may comprise tilting parameters stored in the tilting parameter database 196 (FIG. 3). In certain implementations, the controller 184 receives data indicating the identity of a solidifiable material

selected by a user and uses the identified solidifiable material to query the tilting parameter database 196 and retrieve a set of tilting parameters corresponding to the identified solidifiable material. Illustrative examples of database records in the tilting parameter database 196 will be described further below with reference to FIG. 9. Leveling wait times of no more than about five (5), preferably no more than about three (3), and still more preferably not more than about two (2) seconds are preferred. At the same time, leveling wait times of at least about 0.25, preferably at least about 0.5, and more preferably at least about 0.8 seconds are preferred. In one implementation, a leveling wait time of about one (1) second is used.

[00138] In certain implementations of the method of FIG. 7, it has been found that during the first several layers of an object solidification operation, it may not be possible to obtain sufficient solidifiable material above the exposed object surface to develop a new layer of solidifiable material of the desired layer thickness. In such implementations, the deep dipping process described with respect to FIGS. 1A-1E is preferably implemented for the first several layers of the object. Thus, in accordance with this variation, step 1028 is modified during the formation of the first several layers of the object such that the build platform is dipped in the negative build (z) axis direction by an amount greater than the desired layer thickness Δz and is subsequently elevated in the positive build (z) axis direction until the exposed object surface 82 is spaced apart from the exposed solidifiable material surface by the desired layer thickness Δz. In preferred implementations of this variation, the deep dipping step is carried out during the formation of at least layer 2, more preferably during layers 2-3, still more preferably during layers 2-4, even more preferably during layers 2-5, still more preferably during layers 2-6, yet more preferably during layers 2-7, even more preferably during layers 2-8, and still more preferably during layers 2-9, and yet more preferably during layers 2-10. The deep dipping process is preferably carried out for no more than the first 30 layers, even more preferably no more than the first 20 layers, and still more preferably no more than the first 15 layers. When this deep dipping variation is used, the depth of the deep dipping is preferably at least about 2x, more preferably at least about 10x, more preferably at least about 40x, still more preferably at least about 50x, and yet more preferably at least about 100x the desired layer thickness Δz. At the same time, the depth of the deep dipping is preferably no more than about 400x, still more preferably no more than about

350x, even more preferably no more than about 300x, and even more preferably no more than about 200x the desired layer thickness Δz. Thus, in one example using a desired layer thickness Δz of 50 microns, the deep dipping depth ranges from 5-10mm, which is 100-200 times the layer thickness. In preferred examples, when deep dipping is used, solidification of the next object layer is deferred (step 1034) until the leveling wait time expires after the solidification substrate assembly 57 is in the level configuration and the build platform 46 has been elevated so that the exposed object surface 82 is spaced apart from the solidification substrate assembly 57 by a distance along the build (z) axis equal to the desired layer thickness Δz.

[00139] In accordance with the deep dipping variation, there is preferably a waiting period between the completion of the deep dipping step and the elevation of the build platform 46 to a build (z) axis location at which the exposed object surface 82 (FIGS. 1B-1E) is spaced apart from the exposed solidifiable material surface 51 (FIGS. 1D) by the desired layer thickness Δz. In preferred examples, the waiting period is preferably at least about one (1) second, more preferably at least about 1.5 seconds, and still more preferably at least about 2 seconds. At the same time, the waiting period is preferably no more than about 10 seconds, still more preferably no more than about 8 seconds, and even more preferably no more than about 5 seconds. The deep dipping variation can be performed with or without tilting the solidification substrate assembly or performing the leveling operation described above. However, if tilting is not used to perform an object peeling operation, the speed of descent of the build platform 46 in the negative build (z) axis direction must be reduced because object separation from the film 60 will occur during the descent and without tilting, the separation forces per unit area will generally be higher across the exposed object surface.

[00140] Referring to FIGS. 8A-8B, a second method of making a three-dimensional object using a tilting solidification substrate assembly 57 will now be described. Apparatuses useful for carrying out the method include but are not limited to the apparatuses of FIGS. 1A-6 and 10-13. As with the method of FIG. 7, the method of FIGS. 8A-8B may be carried out by a computer executable process steps stored in the non-transitory memory of the controller and executed by the controller's processor. Leveling wait times of no more than about five (5), preferably no more than about three (3), and still more preferably not more than about two (2) seconds are

preferred. At the same time, leveling wait times of at least about 0.25, preferably at least about 0.5, and more preferably at least about 0.8 seconds are preferred. In one implementation, a leveling wait time of about one (1) second is used.

[00141] In step 1040, object data representative of the three-dimensional object is read. In step 1042 a user's selection of a solidifiable material identifier is read (e.g.,, "Envisiontec E-Denstone"). The material identifier is used as a database query key to retrieve a set of tilting parameters comprising one or more tilting parameters from a tilting parameter database such as the tilting parameter database 196 of FIG. 3. In step 1044, the set of tilting parameters corresponding to the selected solidified material is retrieved. The set of tilting parameters includes one or more of the following, alone or in combination: an actuator peeling distance Δa, a minimum object peeling travel distance Δg, a reference peeling velocity, a reference leveling velocity, a peeling velocity, a leveling velocity, a leveling wait time, and a leveling pressure sensor set point. In addition to or in lieu of the leveling pressure set point, a rate of pressure change (dP/dt) threshold may be provided as a tilting parameter.

[00142] To begin an object building operation, a layer index k is next initialized (step 1046) and then incremented by one (1) (step 1048). In step 1050, the object data is used to identify an x-axis location of solidification that is closest to the tilting axis (i.e., the hinges 74a and 74b in FIGS. 1A-1E, 4A-4E and 6) and farthest from the actuator 66, 166. The expression $f(k)$ in step 1050 refers to the fact that the value of x_{max} depends on the particular layer, and therefore, the value of the layer index k.

[00143] In the method of FIG. 8A, one or more tilting parameter values are calculated based on object data representative of the object. Step 1052 exemplifies such a technique. In this step, the value of the actuator peeling distance Δa is determined for the current layer by determining the peeling distance Δa that would cause the part of the film 60 in contact with the exposed object surface 82 at x_{max} to travel by a linear distance of Δg. In general, points on the film 60 in contact with the exposed object surface 82 at x_{max} will travel in a circular path during peeling operations. The starting location and ending location of the points will define linear vectors between the starting and ending locations, and the value of Δa is selected so that the lengths of these linear vectors are equal to Δg. This technique tunes the amount of peeling to the particular

x-axis profile of each object layer, thereby minimizing the amount of peeling and reducing peeling times. In certain examples, equation (1) may be used to calculate Δa. In an alternative implementation of step 1052, the x-axis coordinate of the build platform location that is closest to the tilting axis and farthest from the actuator is used as x_{max}. In this implementation, the actuator peeling distance Δa is not adjusted based on the object data but may be adjusted based on the solidifiable material by providing values of Δg in a tilting parameter database that vary depending on the material used.

[00144] Step 1054 provides another example of calculating a tilting parameter based on object data. In step 1054 the area of the exposed object surface 82 is calculated from object data representative of the three-dimensional object using known techniques. It is believed that certain tilting parameters are beneficially adjusted based on the exposed surface area of a three-dimensional object. In step 1056 a modified peeling velocity is calculated from a reference (or initial) peeling velocity in the tilting parameter database 196. In one implementation, the reference peeling velocity is based on a reference exposed object surface area, and the modified peeling velocity is calculated by dividing the determined value of the exposed object surface area 82 for the current layer by the reference surface area and multiplying that ratio by the reference peeling velocity. A modified leveling velocity may also be calculated in this manner. However, in general, it is believed that adjusting the peeling velocity based on the exposed object surface area is more beneficial than adjusting the leveling velocity based on it.

[00145] In step 1058 the portions of the exposed solidifiable material surface that are to be solidified ($P(x,y)$) are solidified. The set of $P(x,y)$ will vary with the particular layer, and therefore, with the value of the layer index k. If each y-axis position at x_{max} *has* been solidified, the layer solidification operation is complete and control transfers to step 1062. Otherwise, control returns to step 1058 to continue solidification.

[00146] A peeling operation is commenced in step 1062. A controller such as controller 184 generates a first actuator activation signal having a signal value that corresponds to the modified peeling velocity. In one example, the first actuator activation signal is a variable current, the value of which causes the actuator 66 to extend the distal end 70 of the actuator shaft 68 at the modified peeling velocity. Using the apparatus of FIG. 6, hydraulic fluid is withdrawn from

cylinder 169 at a rate that causes actuator 166 to retract the distal end 170 of actuator shaft 168 at the modified peeling velocity.

[00147] In step 1062 the solidification substrate assembly 57 tilts away from the build platform 46 as shown in FIGS. 1C and 1D. Because the actuator peeling distance Δa is variable in the method of FIGS. 8A and 8B, in step 1064 a determination is made as to whether the actuator distal end 70 has reached the modified actuator peeling distance Δa. If it has, control transfers to step 1066. Otherwise, step 1062 is continued until the modified actuator peeling distance Δa is reached. In certain preferred implementations, step 1062 begins no more than about one (1) second after the completion of a layer solidification operation in step 1058.

[00148] In certain exemplary implementations, step 1062 is carried out using a peeling velocity of at least about 0.1, preferably at least about 0.2, and more preferably at least about 0.3 mm/seconds. At the same time, the peeling velocity is no more than about one (1) mm/second, more preferably no more than about 0.8 mm/second and still more preferably no more than about 0.7 mm/second. In one exemplary implementation, a peeling velocity of 0.5 mm/seconds is used.

[00149] In step 1066 the layer index k is compared to the maximum layer index for the entire object k_{max}. If the maximum index k_{max} has been reached, the object is complete and the method ends. Otherwise, control transfers to step 1070 to begin the process of forming a new layer of solidifiable material. In step 1070 the build platform 46 (FIGS. 1A-1E) is moved away from the rigid or semi-rigid solidification substrate 58 and the film 60 by one layer thickness Δz. As illustrated in FIG. 3, this step may be carried out by having controller 184 issue a signal to the build platform motor to cause it to operate and move the build platform downward by the desired amount. In certain variations of the method of FIGS. 8A and 8B, steps 1070 and 1062 are carried out concurrently. In preferred implementations, the time between the completion of peeling as determined in step 1064 and the commencement of leveling in step 1072 is no more than one (1) second.

[00150] The controller then generates a second actuator signal having a signal value that corresponds to the leveling velocity (or modified leveling velocity if one is calculated from the object data for the layer) (step 1072). Step 1072 causes the solidification substrate assembly 57 to tilt about the tilting axis toward the build platform 46 until reaching the "home" or "level"

position. In certain implementations, controller 184 receives a signal from the build platform motor (not shown) indicating when the platform 46 has stopped in its descent. The leveling operation of step 1030 is carried out either when the signal is received or within a fixed time thereafter. Alternatively, leveling may begin after the expiration of a fixed time from the beginning of the build platform movement or after the expiration of a fixed time after the completion of peeling if the time is selected to ensure that build platform movement is complete before leveling begins. In certain exemplary implementations, step 1072 is carried out using a leveling velocity of at least about 0.1, preferably at least about 0.2, and more preferably at least about 0.3 mm/seconds. At the same time, the leveling velocity is no more than about one (1) mm/second, more preferably no more than about 0.8 mm/second and still more preferably no more than about 0.7 mm/second. In one exemplary implementation, a leveling velocity of 0.5 mm/seconds is used.

[00151] In step 1074 a determination is made as to whether a leveling pressure sensor such as sensors 86 and 110 is present. If one is present, control transfers to step 1078. In step 1078 the method compares the current pressure (or force) sensor reading to the setpoint to determine if the squeezing of solidifiable material is complete. Once the pressure reaches a reference set point, squeezing is considered to be complete and control transfers to step 1048 to begin another layer solidification operation. In another implementation, step 1074 may be carried out by determining the rate of change of the pressure (*dP/dt*) or force (*dF/dt*) and comparing it to a threshold value that indicates when squeezing of solidifiable material is complete.

[00152] If step 1074 indicates that no leveling pressure sensor is present, control transfers to step 1076. In step 1076 the next layer solidification operation is deferred until the expiration of the leveling wait time. Once the leveling wait time expires, control transfers to step 1048 to begin another layer solidification operation. Leveling wait times of no more than about five (5), preferably no more than about three (3), and still more preferably not more than about two (2) seconds are preferred. At the same time, leveling wait times of at least about 0.25, preferably at least about 0.5, and more preferably at least about 0.8 seconds are preferred. In one implementation, a leveling wait time of about one (1) second is used.

[00153] In certain implementations of the method of FIGS 8A-8E, it has been found that during the first several layers of an object solidification operation, it may not be possible to obtain sufficient solidifiable material above the exposed object surface to develop a new layer of solidifiable material of the desired layer thickness. In such implementations, the deep dipping process described with respect to FIGS. 1A-1E is preferably implemented for the first several layers of the object. Thus, in accordance with this variation, step 1070 is modified during the formation of the first several layers of the object such that the build platform is dipped in the negative build (z) axis direction by an amount greater than the desired layer thickness Δz and is subsequently elevated in the positive build (z) axis direction until the exposed object surface 82 is spaced apart from the exposed solidifiable material surface by the desired layer thickness Δz. In preferred implementations of this variation, the deep dipping step is carried out during the formation of at least layer 2, more preferably during layers 2-3, still more preferably during layers 2-4, even more preferably during layers 2-5, still more preferably during layers 2-6, yet more preferably during layers 2-7, even more preferably during layers 2-8, and still more preferably during layers 2-9, and yet more preferably during layers 2-10. The deep dipping process is preferably carried out for no more than the first 30 layers, even more preferably no more than the first 20 layers, and still more preferably no more than the first 15 layers. When this deep dipping variation is used, the depth of the deep dipping is preferably at least about 2x, more preferably at least about 10x, more preferably at least about 40x, still more preferably at least about 50x, and yet more preferably at least about 100x the desired layer thickness Δz. At the same time, the depth of the deep dipping is preferably no more than about 400x, still more preferably no more than about 350x, even more preferably no more than about 300x, and even more preferably no more than about 200x the desired layer thickness Δz. Thus, in one example using a desired layer thickness Δz of 50 microns, the deep dipping depth ranges from 5-10mm, which is 100-200 times the layer thickness. In preferred examples, when deep dipping is used, solidification of the next object layer is deferred (step 1076) until the leveling wait time expires after the solidification substrate assembly 57 is in the level configuration and the build platform 46 has been elevated so that the exposed object surface 82 is spaced apart from the solidification

substrate assembly 57 by a distance along the build (z) axis equal to the desired layer thickness Δz.

[00154] In accordance with the deep dipping variation, there is preferably a waiting period between the completion of the deep dipping step and the elevation of the build platform 46 to a build (z) axis location at which the exposed object surface 82 (FIG. 1D) is spaced apart from the exposed solidifiable material surface 51 by the desired layer thickness Δz. In preferred examples, the waiting period is preferably at least about one (1) second, more preferably at least about 1.5 seconds, and still more preferably at least about 2 seconds. At the same time, the waiting period is preferably no more than about 10 seconds, still more preferably no more than about 8 seconds, and even more preferably no more than about 5 seconds. The deep dipping variation can be performed with or without tilting the solidification substrate assembly 57 or performing the leveling operation described above. However, if tilting is not used to perform an object peeling operation, the speed of descent of the build platform 46 in the negative build (z) axis direction must be reduced because object separation from the film 60 will occur during the descent and without tilting, the separation forces per unit area will generally be higher across the exposed object surface.

[00155] As discussed previously, in certain implementations of the apparatuses and methods described herein, one or more tilting parameters are provided in a tilting parameter database 196 (FIG. 3). The tilting parameter database 196 preferably associates a set of tilting parameters comprising at least one tilting parameter with one of several various solidifiable materials. A user may then select a material identifier on a computer user interface provided with the apparatus. Computer executable program instructions stored in the controller memory 186 then use the selected material to query the tilting parameter database 196. The query returns the set of tilting parameters associated with the selected material identifier which is then used to carry out tilting operations. FIG. 9 depicts three exemplary records of a tilting parameter database 196. In the depicted example, three solidifiable material identifiers are provided 214a-214c. Each record associates a minimum object peeling travel distance 216b *(Δg)*, a peeling velocity 216c, a leveling velocity 216d, a leveling wait time 216e, and a reference squeezing pressure 216f with one of the solidifiable material identifiers 215a-215c. Thus, a user wishing to build an object

with Envisiontec E-Denstone would make a corresponding entry into a user interface provided with the apparatus for making a three-dimensional object. The selected entry would be transmitted to the controller 184 and used by the computer executable process instructions to perform a database query and retrieve the tilting parameter values in the first row of the table (FIG. 9). In certain variations of the tilting parameter database 196, the peeling velocity is a reference peeling velocity based on a particular exposed object surface area and is used by the computer executable program instructions stored in the controller memory 186 to calculate a modified peeling velocity based on a determined exposed object surface area for the layer of interest. In another variation, a fixed actuator peeling distance Δa *is* used in lieu of one calculated from a minimum object peeling distance Δg.

[00156] The use of the tilting parameter database 196 allows tilting parameters to be adjusted based on the particular materials used to make a solidifiable object. This tuning of the tilting process to the solidifiable material avoids the need for setting fixed tilting parameters that should function for all potential solidifiable materials which can result in excessive object build times.

[00157] Referring to FIGS. 10-13, another exemplary solidification substrate assembly 57 and work table 64 are depicted for use in an apparatus for making at three-dimensional object such as apparatus 40 of FIGS. 1A-1E. Like numerals in FIGS. 10-13 refer to like components in FIGS. 1A-1E, 4A-4E, 5A-5C and 6. Unlike the other apparatuses, however, in the example of FIGS. 10-13 two actuators 266a and 266b are providing for tilting the solidification substrate assembly 57 about a tilt axis defined by hinges 74a and 74b (not shown in FIGS. 10-13, but shown in FIG. 4D on side 65a of work table 64.

[00158] Actuators 266a and 266b are spaced apart along the y-axis. Actuator 266a includes a housing 267a and a shaft 268a (not visible in the figures). Actuator housing 267a includes a proximal end 220a, and shaft 268a includes a distal end 270a. A portion of shaft 268a is disposed in actuator housing 267a and guide bushing 206a. Guide bushing 206a is fixedly attached to and stationary with respect to actuator housing 267a. However, the spacing between the guide bushing 206a and the distal end 270a of shaft 268a is adjustable when the actuator 266a is adjusted between an extended configuration and a retracted configuration (and vice-versa). Guide bushing 206a is provided to facilitate the adjustment of the actuator 266a from a

retracted configuration to an extended configuration and reduces the amount of vibration occurring during the adjustment process. In the retracted configuration, the actuator length defined by the distance between the actuator housing proximal end 220a and the distal shaft end 270a is smaller than the distance between the actuator housing proximal end 220a and distal shaft end 270a when actuator 266a is in the extended configuration.

[00159] Similarly, actuator 266b includes a housing 267b and a shaft 268b (visible in FIG. 13). Actuator housing 267b includes a proximal end 220b, and shaft 268b includes a distal end 270b. A portion of shaft 268b is disposed in actuator housing 267b and guide bushing 206b. Guide bushing 206b is fixedly attached to and stationary with respect to actuator housing 267b. However, the spacing between guide bushing 206b and the distal end 270b of shaft 268b is adjustable when the actuator 266b is adjusted between an extended configuration and a retracted configuration (and vice-versa). Guide bushing 206b is provided to facilitate the adjustment of the actuator 266b from a retracted configuration to an extended configuration (and vice-versa) and reduces the amount of vibration occurring during the adjustment process. In the retracted configuration, the actuator length defined by the distance between the actuator housing proximal end 220b and the distal shaft end 270b is smaller than the distance between the actuator housing proximal end 220b and distal shaft end 270b when actuator 266b is in the extended configuration. In the extended configuration, the distance along the build (z) axis from the actuator proximal ends 220a, 220b to the build platform (not shown in FIGS. 10-13, but shown in FIGS. 1A-1E) is greater than in the retracted configuration.

[00160] In FIG. 10 the solidification substrate assembly 57 is shown in a level configuration as would be the case following a leveling operation. The linear solidification device 62 may solidify solidifiable material underneath film assembly 90 as it moves in either or both directions along the x-axis. In FIG. 11 the solidification substrate assembly 57 is shown in an open configuration that is not used during the manufacture of a three-dimensional object.

[00161] Unlike the examples of FIGS. 1A-1E, 4A-4E, and 6, in the example of FIGS. 10-13, the actuator distal ends 270a and 270b remain fixed with respect to work table 64 while making a three-dimensional object from a solidifiable material. However, the actuator housings 267a and 267b and their respective proximal ends 220a and 220b are movable along the build (z) axis

relative to work table 64. Thus, in the example of FIGS. 10-13, the actuator peeling distance Δa, for each actuator is equal to the distance of travel of each actuator proximal end 220a and 220b along the length axis of its respective shaft 268a and 268b during an object peeling operation. The length axes of actuator shafts 268a and 268b are generally parallel to the build (z) axis and are substantially parallel to the build (z) axis when the solidification substrate assembly 57 is in a level configuration (as shown in FIG. 10). However, the actuator shaft 268a and 268b length axes will tilt during a solidification substrate assembly 57 tilt operation because the solidification substrate assembly 57 traverses a circular path when viewed along the y-axis during a tilting operation. The actuator shafts 268a and 268b will exhibit their maximum degree of tilt relative to the build (z) axis when their respective actuator proximal housing ends 273a and 273b reach their fully extended positions.

[00162] To provide the foregoing configuration, latches 214a and 214b are mounted on the work table 64. A detailed view of latch 214b and its related components is shown in FIG. 13. Latch 214a is configured and operates similarly with analogous components. Referring to FIG. 13, latch shaft 222b is slidable in groove 226b within latch 214b to selectively attach distal shaft end 270b to work table 64 or detach distal shaft end 270b from work table 64, as desired. Latch shaft 222b preferably has a knob such as knob 116 in FIGS. 4B and 4C, but the knob is not shown in FIG. 13. The distal end 270b of actuator shaft 268b includes an opening that can selectively receive latch shaft 222b to attach distal end 270b to the latch 214b, thereby attaching distal shaft end 270b to the work table 64. In FIG. 13, latch 214b is in a latched condition, with latch shaft 222b extending through an opening in shaft distal actuator end 270b and an opening in latch 214b. Although not visible in the figures, latch 214a is configured similarly to allow distal shaft end 270a to be selectively attached to or detached from the work table 64. In FIG. 11, latches 214a and 214b are shown in an unlatched condition.

[00163] Actuators 266a and 266b may be energized by motors or by hydraulic power. In either case, during an object peeling operation, the actuator housings 267a and 267b move upward along their respective shaft length axes and along the build (z) axis relative to work table 64 and build platform 46 (FIGS. 1A-1E). During a leveling operation, the actuator housings 267a and 267b move downward along their respective shaft length axes and the build (z) axis

relative to work table 64 and build platform (FIGS. 1A-1E). The movement of the actuator housings 267a and 267b along the build (z) axis causes the load frame 120 to tilt about the tilt axis defined by hinges 74a-74b (not shown in FIGS. 10-13, but shown in FIG. 4D) which also causes the remainder of the solidification substrate assembly 57 to tilt about the tilt axis.

[00164] As best seen in FIG. 13, actuator housing 267b is connected to the load frame 120 via vertical actuator support 205b and horizontal support 203b. Bracket 221b is connected to proximal actuator end 220b at a pivot axis 223b which allows the actuator 266b to pivot relative to bracket 221b, horizontal actuator supports 203b, and vertical actuator support 205b. This pivoting action allows the actuators 266a and 266b to tilt such that their respective length axes tilt relative to the build (z) axis during solidification substrate assembly 57 tilting operations as the solidification substrate assembly traverses a circular path when viewed along the y-axis.

[00165] As actuator 266b is adjusted from a retracted configuration to an extended configuration (during an object peeling operation), the actuator proximal end 220b exerts an upward (build (z) axis) force against bracket 221b, which in turn exerts an upward force against horizontal actuator support 203b. The horizontal actuator support 203b exerts an upward (build (z)) axis force against the vertical actuator support 205b, which in turn exerts an upward (build(z)) axis force against the side 95d (FIGS. 12A and 12B) of load frame 120 to tilt the load frame 120 about the tilt axis defined by hinges 74a-74b (FIG. 4D). Actuator housing 267a is connected to load frame 120 in a similar manner by a bracket 221a and actuator supports 203a and 205a which are not shown in FIG. 13.

[00166] In FIG. 10, the actuator proximal end brackets 221a and 221b are configured somewhat differently from those shown in FIG. 13. In addition, the actuators 266a and 266b in FIG. 10 do not have individual horizontal supports 203a and 203b connecting the actuators 266a and 266b to vertical actuator supports 205a and 205b, respectively. Instead, a cross-beam 202 is provided and is attached to brackets 221a and 221b, respectively, and to the actuator vertical supports 205a and 205b, respectively. The guide bushings 206a and 206b are fixedly attached to their respective actuators 266a and 266b. The guide bushing holder 218 is connected to the vertical actuator supports 205a and 205b. Thus, during an object peeling or leveling operation, the guide bushing holder 218 and the guide bushings 206a and 206b preferably move along the

build (z) axis relative to the work table 64, build platform 46 (FIGS. 1A-1E) and relative to the distal actuator ends 270a and 270b.

[00167] As best seen in FIGS. 12A and 12B, load frame brackets 212a and 212b are provided on side 95d of load frame 120 and are sized to overlap with work table side 65b along the x-axis. The load frame brackets 212a and 212b act as stops to restrain the downward build (z) axis movement of the solidification substrate assembly 57. In addition, load frame bracket 212b is positioned to engage pressure (or force) sensor 110 attached to work table side 65b. As with the examples of FIGS. 4A-4E, and 6, the solidification substrate assembly 57 and work table 64 of FIGS. 10-13 may be used in apparatus 40 of FIGS. 1A-1E, in which case each new layer of solidifiable material will be provided between an exposed object surface (such as surface 82 in FIGS. 1B-1D) and film 60 of film assembly 90. The solidifiable material 50 in the space between the exposed object surface 82 and film 60 will exert an upward force and pressure that will decrease the force or pressure sensed by the pressure (or force) sensor 110. The upward force exerted by the solidifiable material 50 will decrease as solidifiable material is squeezed out of the space between the exposed object surface 82 and the film 60 until reaching an equilibrium value.

[00168] As shown in FIGS. 12A and 12B, bracket 212a includes a screw 213a with an adjustable length along the build (z) axis which allows the stop position of the load frame 120 along the build (z) axis on a first y-axis side of the load frame 120 to be selectively adjusted. Correspondingly, bracket 212b includes a screw 213b with an adjustable length along the build (z) axis which allows the stop position of the load frame 120 on a second y-axis side of the load frame 120 to be selectively adjusted. In certain examples, the screws 213a and 213b are adjusted to ensure that the solidification substrate 58 defines a plane that is substantially or completely perpendicular to the build (z) axis and parallel to the x-y plane.

[00169] Controller 184 of FIG. 3 may be used with the solidification substrate assembly 57 and work table 64 of FIGS. 10-13 and may be configured with the same inputs and outputs. However, outputs 194 are preferably configured to provide outputs to both actuators 266a and 266b. In the case of hydraulic actuators, separate hydraulic pumps and conduits may be provided for each actuator 266a and 266b (in which case the housings 267a and 267b would be

hydraulic cylinders), and the controller outputs 194 may include separate outputs for each pump or a common output provided to each pump. Alternatively, a single pump may supply fluid to both actuators 266a and 266b. In the case of motor-driven actuators, separate motors may be provided for each actuator 266a and 266b, and outputs 194 may include separate outputs for each motor or a common output provided to each motor. In either case, the controller 184 and the source of motive power for actuators 266a and 266b are preferably configured so that the actuator housings 267a and 267b move along the build (z) axis at the same rate relative to one another to avoid the exertion of uneven forces against load frame 120 along the y-axis.

[00170] The two actuator design of FIGS. 10-13 is particularly useful for larger build envelope machines to ensure that the solidification substrate assembly 57 may be stably tilted about the tilting axis. It is also sometimes useful to use two linear solidification devices positioned adjacent one another along the y-axis for larger build envelope machines instead of linear solidification device 62. An example of such a dual linear solidification device configuration is provided in FIG. 36 and paragraphs 0266-271 of U.S. Patent Application No. 13/774,355, the entirety of which is hereby incorporated by reference.

[00171] The methods of FIGS. 7, 8A and 8B may be readily adapted for use with the apparatus of FIGS. 10-13. In certain examples, the actuator activation signals are provided to a source of motive power (e.g., an electric motor or hydraulic fluid pump) used to adjust the length of the actuators 266a and 266b along the build (z) axis as the actuators 266a and 266b are adjusted from a retracted to an extended configuration (and vice-versa). For example, the method of FIG. 7A may be carried out as described previously. However, step 1022 would be modified to generate two first actuator activation signals for each of actuator 266a and 266b (or by supplying the same signal to each actuator). The determination of whether peeling is complete in step 1024 may be made by using a limit switch associated with either or both actuators 266a and 266b or based on the operation of the respective motors or hydraulic pumps. Step 1030 would be modified to generate two second actuator activation signals for each of actuator 266a and 266b or to generate a single actuator activation signal provided to each actuator 266a and 266b. Pressure (or force) sensor 110 may be used to carry out step 1032, or alternatively, a leveling wait time may be used.

[00172] Referring to FIGS. 8A and 8B, in step 1052 the calculated actuator peeling distance Δa used may be used to determine the extent that the respective actuator housings 267a and 267b will move along the length axes of their respective actuator shafts 268a and 268b relative to their respective distal shaft ends 270a and 270b and the work table side 65b (as well as relative to a build platform such as the build platform 46 of FIGS. 1A-1E). In step 1062, respective actuator activation signals (or a common actuator activation signal) may be provided to the sources of motive power (e.g., motors or hydraulic pumps) to adjust the rate at which the lengths of the actuators 266a and 266b change to correspond to the modified peeling velocity determined in step 1056. Step 1064 may be carried out by determining whether the change in the lengths of either or both actuators 266a and 266b have reached the calculated peeling distance Δa. Step 1072 may be carried out by generating two actuator activation signals for the respective sources of motive power used to adjust the lengths of actuators 266a and 266b from the extended configuration to the retracted configuration. Alternatively, a common actuator activation signal may be supplied to the source of motive power for each actuator 266a and 266b.

[00173] In certain exemplary implementations, the actuators 266a and 266b apply a constant force against the solidification substrate assembly 57 (by virtue of their connection to vertical actuator supports 205a and 205b) during an object peeling operation. In other exemplary implementations, the actuators 266a and 266b apply a constant force against the solidification substrate assembly 57 during a leveling operation. In further exemplary implementations, the actuators 266a and 266b apply a constant force against the solidification substrate assembly 57 during both an object peeling operation and a leveling operation (albeit in opposite directions). In a preferred method, the same constant force is applied to the solidification substrate assembly 57 during an object peeling and a leveling operation (in opposite directions) and the constant force (in the negative build (z) axis direction) used in the leveling operation remains after the solidification substrate assembly 57 is level, which stabilizes the assembly 57 against the upward pressure of the solidifiable material. In one example, a constant force of 80 psi is applied to the solidification substrate assembly 57 during both an object peeling and a leveling operation.

[00174] In certain preferred examples, when solidification substrate assembly 57 is in a level configuration and solidification of the next layer of solidifiable material 50 has not yet begun,

actuators 266a and 266b apply a level configuration force, as described previously with the examples of FIGS. 1A-1E, 4A-4E, and 6 and as illustrated in FIGS. 14A and 14B. In the case of actuators 266a and 266b, the level configuration force is applied by applying a downward force in the build (z) axis direction against the brackets 221a and 221b, which in turn applies an downward force in the build (z) axis direction against the vertical actuator supports 205a and 205b, each of which is connected to the load frame 56.

[00175] In certain examples, the tiltable solidification substrate assemblies 57 described herein and illustrated in FIGS. 1A-1E, 4A-4E, 6, 10-13, and 16A-16F are particularly beneficial when the solidifiable material 50 is of a relatively higher viscosity than a relatively lower viscosity. Preferred solidifiable material 50 viscosities (at 25°C) are at greater than 1500 cp, more preferably at least about 1800 cp, still more preferably at least about 2000 cP, even more preferably at least about 2500 cp, and yet more preferably at least about 2800 cP. As explained previously, during a leveling operation, solidifiable material 50 is "squeezed out" of the space between the most recently formed object surface 82 (FIG. 1E) and the solidification substrate assembly 57. In some examples, it is preferable to wait until the flow and movement of solidifiable material 50 between the exposed object surface 82 and the solidification substrate assembly 57 has substantially or completely stopped following a leveling operation. In some embodiments, the solidification of a next layer of solidifiable material 50 is deferred until the expiration of a leveling wait time (FIG. 9) to better ensure that the localized flow and movement of the solidifiable material 50 between the exposed object surface 82 and the solidification substrate assembly 57 has substantially or completely stopped. Without wishing to be bound by any theory, it is believed that the flow and movement of higher viscosity solidifiable materials tends to stabilize more rapidly than that of lower viscosity materials following a leveling operation. In certain preferred examples, the flow and movement of higher viscosity solidifiable materials with viscosities in the range described above between the exposed object surface 82 and the solidification substrate assembly substantially or completely stops at leveling wait times that are no more than about 20 seconds, preferably no more than about 15 seconds, and still more preferably no more than about 10 seconds.

[00176] In certain examples, controller 184 (FIG. 3) includes a program that comprises a set of computer executable steps stored in non-transitory medium 186 that operates the tiltable solidification substrate assemblies 57 described herein in two different modes, depending on the viscosity of the solidifiable material 50. In one example, a viscosity threshold is selected and used to classify solidifiable material 50 has a "low viscosity material" or a "high viscosity material." When executed by processor 188, the computer executable steps receive data indicating whether the solidifiable material 50 is a low viscosity material or a high viscosity material. If the solidifiable material 50 is a low viscosity material, the controller 184 operates in a "low viscosity mode", in which computer executable steps cause the actuator (66, 166, 266) to apply a level locking force to the solidification substrate assembly 57 that locks the solidification substrate assembly 57 in a level configuration. The level locking force may be constant or variable. In certain examples, the level locking force is higher during an object solidification operation (e.g., when linear solidification device 62 is traveling along the travel (x) axis and projecting solidification energy along the scanning (y) axis) than during all or part of the period when an object solidification operation is not occurring. In other examples, the level locking force follows one of the patterns shown in phase B in FIGS. 14A and 14B when an object solidification operation is not occurring and follows the pattern shown in phase C during an object solidification operation.

[00177] In some examples of the low viscosity mode, "deep dipping" operations may be required to supply a sufficient amount of solidifiable material between the most recently formed exposed object surface 82 and the solidification substrate assembly 57. In certain cases in which the actuator 66, 166, 266a/b is motor-driven, the level locking force is preferably higher during all or part of the time during which the build platform 46 is moved upward along the build (z) axis toward the solidification substrate assembly 57 than after the build platform 46 has reached a position at which the most recently formed exposed object surface 82 is spaced apart from the solidification substrate assembly 57 by the desired layer thickness Δz.

[00178] In certain low viscosity operation examples wherein the actuators 66, 166, 266a/b are motor-driven, the actuator motor electrical loads may follow the load patterns depicted in FIGS. 14A and 14B. In such cases, phase "A" represents the period during which the build platform 46

is moving upward along the build (z) axis toward the solidification substrate assembly 57, phase "B" represents the period during which (1) no solidification is occurring and (2) the build platform 46 has stopped moving and is positioned so that the exposed object surface 82 (FIG. 1E) is spaced apart from the solidification substrate assembly 57 by the desired layer thickness Δz, and phase "C" represents the period during which an object solidification operation is occurring and the build platform 46 remains spaced apart from the solidification substrate assembly by the desired layer thickness Δz.

[00179] In accordance with the foregoing, when controller 184 receives data indicating that the solidifiable material 50 is a "high viscosity material," the processor 188 will execute a set of computer executable steps stored in non-transitory memory 186 which will cause the actuators 66, 166, and 266a/b to carry out object peeling and leveling operations as described previously herein. The controller 184 may also apply a level configuration force to solidification substrate assembly 57 when the substrate 58 is level and no object solidification is occurring such that the level configuration force differs from the force applied during a leveling operation and during an object solidification operation. In certain examples, controller 184 executes the computer executable process steps applicable to a low viscosity material when the controller 184 receives data indicating that the viscosity of the solidifiable material (at 25°C) is no more than 1500 cp, more preferably less than about 1200 cp, and still more preferably less than about 1000 cp. The controller 184 may receive actual viscosity data or may instead may be programmed to select the low viscosity mode of operation or the high viscosity mode of operation based on a material identifier of the type shown in FIG. 9. In certain examples, the "low viscosity mode" of operation is used for those materials that still experience appreciable flow and movement more than about 20 seconds, more preferably more than about 15 seconds, and still more preferably more than about 10 seconds after a leveling operation is complete. Otherwise, the "high viscosity" mode of operation is used.

[00180] Referring to FIG. 15, a dual-mode method of making a three-dimensional object from a solidifiable material using an apparatus with a tiltable solidification substrate assembly is depicted. The method of FIG. 15 includes two modes of operation, one for "high viscosity" solidifiable materials and one for "low viscosity" solidifiable materials. The method may be

used, for example, with any of the tiltable solidification substrate assemblies 57 shown in FIGS. 1A-1E, 4A-4E, 10-13, and 16A-16F. In certain examples, "high viscosity" materials are those that substantially stabilize so that no localized flow occurs between the exposed object surface 82 and the solidification substrate assembly 57 within a specified leveling wait time after the solidification substrate assembly 57 assumes a level configuration. In certain examples, the specified leveling wait time is no more than about 20 seconds, preferably no more than about 15 seconds, and still more preferably not more than about 10 seconds.

[00181] In the same or other examples, "high viscosity" materials are those with a viscosity at 25°C that is greater than 1500 cp, more preferably at least about 1800 cp, still more preferably at least about 2000 cP, even more preferably at least about 2500 cp, and yet more preferably at least about 2800 cP. In step 1082 a determination is made as to whether the solidifiable material 50 is high viscosity. In certain examples, controller 184 (FIG. 3) is provided and receives data indicative of the viscosity of the solidifiable material 50. The data may be viscosity data. It may also be a solidifiable material identifier such as those shown in field 216a of FIG. 9, which is then identified as a high or low viscosity material via another database accessed by controller 184.

[00182] In step 1082 if the solidifiable material 50 is a high viscosity material, control transfers to step 1084 to initialize the layer index *k*. In step 1084 the layer index *k* is incremented. In step 1088 a layer of thickness Δz (FIG. 1E) is solidified. In examples where a linear solidification device 62 is provided, the solidification of a layer is carried out by traversing the linear solidification device 62 along the travel (x) axis while supplying solidification energy along the scanning (y) axis. For SLM based methods, one or more two-dimensional solidification energy patterns will be projected as an image onto the exposed surface 51 of the solidifiable material to carry out step 1088.

[00183] In step 1090 an object peeling operation is carried out by tilting the solidification substrate assembly 57 about the tilting axis (e.g., hinges 74a and 74b in FIGS. 1A-1E, 4A-4E, 6 and 10) in a direction away from build platform 46. Step 1090 will separate the solidification substrate assembly 57 from the exposed object surface 82. Thus, in step 1092 the method determines if the last layer of the object has been solidified by comparing the current value of the

layer index k to the maximum value k_{max}. If solidification is complete, the method ends. Otherwise, control transfer to step 1094.

[00184] In step 1094 build platform 46 is moved away from solidification substrate assembly 57 in direction along the build (z) axis by an amount that is at least equal to the next desired layer thickness Δz. In certain cases, it may be desirable to use "deep dipping" for all or part of the object building process, in which case the build platform 46 will initially move away from the solidification substrate assembly 57 by along the build (z) axis bv an amount that is greater than the next desired layer thickness Δz and then moved back toward the build (z) axis to a position where the exposed object surface is spaced apart from the level configuration position of the solidification substrate assembly 57 by the desired layer thickness Δz. Step 1094 may be carried out concurrently with step 1090, but is preferably carried out after step 1090. In step 1096 a leveling operation is carried out by tilting the solidification substrate assembly about the tilting axis toward the build platform 46.

[00185] In step 1098 the method waits for the expiration of a "leveling wait time" so that the flow of solidifiable material 50 between the exposed object surface 82 and the solidification substrate assembly 57 substantially or completely stops. Step 1098 preferably begins when the solidification substrate assembly 57 is in the level configuration and the exposed object surface 82 is spaced apart from the solidification substrate assembly 57 by the desired layer thickness and ends after the leveling wait time has elapsed. Following step 1098, control transfers to step 1086 and the layer index k is incremented to begin the solidification of the next layer. If a motor driven actuator (or actuators) is used, during step 1098, level configuration forces may be applied as described previously with respect to the apparatuses of FIGS. 1A-1E and 4A-4E and as further illustrated in FIGS. 14A-B.

[00186] If step 1082 returns a value of NO ("N"), the solidifiable material is a "low viscosity material" and control transfers to step 1100 to initialize the layer index k. In step 1102 the layer index k is incremented. In step 1104 the current layer is solidified as described previously for step 1088. In step 1106 the build platform 46 is moved away from the solidification substrate assembly 57 in a direction along the build (z) axis as in step 1092. For low viscosity materials, since object peeling operations are not used, the most recently formed exposed object surface 82

is separated from the solidification substrate assembly 57 (e.g., from the film 60 or rigid/semi-rigid substrate 58) during step 1106. In general, the speed of descent of the build platform 46 in the negative build (z) axis direction in step 1106 must be reduced relative to step 1094 because object separation from the film 60 will occur during the descent and without tilting, the separation forces per unit area will generally be higher across the exposed object surface. Step 1106 may be carried out using the deep dipping techniques described previously for some or all of the object layers.

[00187] In step 1108 the method determines whether the last layer has been solidified, in which case the layer index k will equal the maximum value k_{max} of the layer index k. If the last layer has been reached, the method ends. Otherwise, control transfers to step 1110.

[00188] Step 1110 begins when the build platform 46 is positioned so that the exposed object surface 82 is spaced apart from the solidification substrate assembly 57 by a distance along the build (z) axis equal to the layer thickness Δz. The step ends once the squeezing time (comparable to a leveling wait time when tilting is not used) expires. During all or part of step 1110, a level locking force may be applied to the solidification substrate assembly 57 in step 1110 which is less than the level locking force used during step 1104, as described previously with respect to FIGS. 14A and 14B.

[00189] In certain examples of the apparatuses for manufacturing three-dimensional objects described herein, the solidification substrate assembly 57 may include a solidification substrate laminate 298 instead of a film assembly 90. Certain types of solidifiable materials 50 have a degree of brittleness (when solidified) which causes them to break when separating from film 60 of film assembly 90. This is particularly the case for finely dimensioned structures such as removable object supports used to connect the object 78 to build platform 46 (FIGS. 1A-1E). In the example of FIGS. 1A-1E, 4A-4E, 6, and 10-13, film 60 is supported by a frame but is not bonded to the rigid or semi-rigid solidification substrate 58. As a result, during an object peeling operation, the film 60 will deform along the build (z) axis and then quickly and resiliently separate from the object 78 in an abrupt manner which can damage the object 78, and in particular, finely dimensioned object structures.

[00190] Referring to FIGS. 16A-16F, a modified version of the apparatus for making three-dimensional objects of FIGS. 4A-4E is depicted. Like numerals in FIGS. 16A-16F and 4A-4E refer to like parts. The apparatus of FIGS. 16A-16F includes the actuator 66 and latch 114 configuration of FIGS. 4A-4E, and the load frame 120 is hinged to the work table 64 in the same manner. The apparatus of FIGS. 16A-16F would also be provided with a solidifiable material container 44 and build platform 46 as shown in FIGS. 1A-1E as well as the controller 184 and associated inputs and outputs shown in FIG. 3.

[00191] In FIGS. 16A-16F, the solidification substrate assembly 57 includes a solidification substrate laminate 298 but does not include the film assembly 90 of FIGS. 4A-4E. The solidification substrate laminate 298 includes a rigid or semi-rigid solidification substrate 58 that is transparent and/or translucent. However, one or more films or coatings are adhered to the rigid or semi-rigid solidification substrate to create a layered or laminate structure. The solidification substrate laminate 298 is operatively connected to at least one actuator and is tiltable within the open top 47 of solidifiable material container 44 about a tilting axis defined by hinges 74a and 74b (FIG. 4D).

[00192] Exemplary illustrations of solidification substrate laminate 298 are provided in FIGS. 17A-17C. Solidification substrate laminate 298 is depicted in an exaggerated perspective view to better illustrate layers 58, 300, and 302. A typical exemplary laminate 298 will be significantly thinner and flatter than shown in the figure. In each of the examples of FIGS. 17A-17C, solidification substrate laminate 298 comprises rigid or semi-rigid solidification substrate 58, which is described above. Each solidification substrate laminate 298 includes an object contacting surface 301 that faces the closed bottom 45 of solidifiable material container 44. However, the materials comprising object contacting surface 301 may vary as described below.

[00193] In certain examples, solidification substrate laminate 298 is provided with a localized area of resiliency proximate the exposed surface 51 (FIGS. 1C and 1D) of solidifiable material 501. Referring to FIGS. 17A and 17C, a transparent and/or translucent resilient layer 300 is provided. A variety of different translucent and/or transparent resilient materials may be used for layer 300. When provided as a 10 mm layer, the resilient layer 300 preferably transmits at least about 60 percent of received light in the 325-700 nm range. The resilient layer 300

preferably has a 10mm layer transmission percentage of at least about 70 percent, more preferably at least about 80 percent, and even more preferably at least about 88 percent for light in the 325-700 nm range. The resilient layer 300 preferably also has a percent elongation at break (according to ISO 37) that is at least about 80 percent, more preferably at least about 90 percent, even more preferably at least about 95 percent, and still more preferably at least about 100 percent. In addition, resilient layer 300 preferably has a tensile strength (according to DIN ISO 37) that is at least about 3.0 N/mm^2, more preferably at least about 5.0 N/mm^2, even more preferably at least about 6.0 N/mm^2, and still more preferably at least about 7.0 N/mm^2.

[00194] Resilient layer 300 may be formed from one or more elastomeric polymers. In one example, silicone elastomers are provided. One particular example of a suitable silicone elastomer is Elastosil® RT 601, which is supplied by Wacker Silicones. Elastosil® RT 601 is a transparent, addition-curing silicone rubber having greater than 88 percent transmission of light in the 325-700nm range (for a 10 mm layer). The material has an elongation at break of about 100 percent (ISO 37), and a tensile strength of about 7.0 N/mm2 (DIN ISO 37) tear strength (ASTM D 624B) of about 3.0 N/mm^2. Resilient layer 300 may be connected to rigid or semi-rigid solidification substrate 58 (FIG. 17A) using known techniques. In one example, an adhesive such as a pressure sensitive adhesive is used to bond resilient layer 300 and rigid or semi-rigid solidification substrate 58 together. The adhesive preferably does not significantly alter the wavelengths of intensities of electromagnetic radiation transmitted through substrate 58.

[00195] Certain solidifiable materials 50 may include components that chemically degrade resilient layer 300. For example, when certain photoinitiators are used to cure polymeric resins, the solidification process may be damage layer 300. Accordingly, in certain examples and as shown in FIG. 17A, a translucent and/or transparent protective layer 302 is provided. Translucent protective film 302 is preferably a homopolymer or copolymer formed from ethylenically unsaturated, halogenated monomers. Fluoropolymers are preferred. Examples of suitable materials for protective film 302 include polyvinylidene fluoride (PVDF), ethylenchlorotrifluoroethylene (ECTFE), ethylenetetrafluoroethylene (ETFE), polytetrafluoroethylene (PTFE), perfluoroalkoxy (PFA), and modified fluoroalkoxy (a copolymer of tetrafluoroethylene and perfluoromethylvinylether, also known as MFA).

Examples of suitable protective film 302 materials include PVDF films sold under the Kynar® name by Arkema, ECTFE films sold under the Halar® name by SolvaySolexis, ETFE films sold under the Tefzel® name by DuPont, PFA films sold under the Teflon® -PFA name by DuPont, and MFA films sold under the name Nowofol.

[00196] In one example, solidification material 50 (FIGS. 1A-1E) comprises a 1,6 hexanediol diacrylate and/or trimthelolpropane triacrylate (TMPTA) with an acylphosphine oxide initiator, such as Irgacure 819. Without wishing to be bound by any theory, it is believed that the photopolymerization/photocrosslinking reaction that occurs generates an amount of heat that can damage resilient layer 300. Accordingly, in such examples an MFA protective film layer 302 is provided to reduce the effect of the generated heat on translucent resilient layer 300. In another example, solidification material 50 comprises 1,6 hexanediol diacrylate and/or TMTPA with a Darocur TPO initiator. Again, it is believed that the photopolymerization/photocrosslinking reaction generates an amount of heat that may damage elastomeric translucent layer 300. Accordingly, in such examples, an MFA protective film layer 302 is provided. Protective layer 302 may be bonded to resilient layer 300 with an adhesive, such as a pressure sensitive adhesive. The adhesive preferably does not significantly alter the wavelengths of intensities of electromagnetic radiation transmitted through solidification substrate laminate 298.

[00197] In certain cases, the force required to separate a solidified section of object 78 from solidification substrate laminate 298 will be low enough that the resiliency provided by resilient layer 300 will not be required. However, protective film 302 may still be used to protect the rigid or semi-rigid solidification substrate 58. Referring to FIG. 17B, a solidification substrate laminate 298 is provided which comprises rigid or semi-rigid solidification substrate 58 and translucent and/or transparent protective film 302. In certain examples a slipping agent is included in the composition of solidifiable material 50, allowing for better release of solidified object 78 from solidification substrate 58, eliminating the need for a resilient layer. Suitable slipping agents include TEGORAD 2250 from the Degussa Company and silicone agent EFKA 7454 from the EFKA Company. In certain other cases, the photopolymerization/photocrosslinking reaction proceeds without damaging the resilient translucent and/or transparent layer 300 or rigid or semi-rigid solidification substrate 58 through

the generation of excess heat or otherwise. In such cases, protective film 302 is not required. Referring to FIG. 17C, a solidification substrate laminate 298 is provided which comprises a rigid or semi-rigid translucent and/or transparent solidification substrate 58 and an elastomeric translucent and/or transparent layer 300. In one example, a resin such as TMPTA, IBOA, or Ebecryl 3500 is used with an Irgacure 784 initiator and no protective film is required.

[00198] Referring again to FIGS. 16A-16F, solidification substrate laminate frame 388 is provided and releasably secures solidification substrate laminate 298 to the solidification substrate assembly 57. The solidification substrate laminate frame 388 is shown in greater detail in FIGS. 16C and 16D. Solidification substrate laminate frame 388 is generally rectangular and made from a rigid metal or plastic. Sidewalls 391a and 391b are spaced apart along the y-axis, and sidewalls 389a and 389b are spaced apart along the x-axis. Cross members 94c and 94d are spaced apart along the x-axis and also include knobs 97a-97b and 96a-96b for securing the solidification substrate laminate frame 388 to the load frame 120 (FIGS. 16A-16B). Latches 392a and 392b are attached to solidification substrate laminate frame sidewalls 389a and 389b, respectively, via respective openings 402a (not shown) and 402b (FIGS. 16C). Each latch 392a and 392b is also connected to a corresponding clamp member 390a and 390b. The clamp members 390a and 390b each have respective openings 403a and 403b which receive and secure latch fastener members 400a and 400b. The latch fastener member 400a extends through solidification substrate laminate frame side wall opening 402a (not shown) and into clamp member opening 403a. Latch fastener member 400b extends through solidification substrate laminate frame side wall opening 402b and into clamp member opening 403b.

[00199] As shown in FIG. 16C, each clamp member 390a and 390b has respective horizontal lip 394a and 394b and a respective vertical wall 396a and 396b. The sidewalls 389a and 389b each have a respective lower surfaces 395a and 395b (FIGS. 16C-16F). Each lip 394a and 394b and its corresponding side wall lower surface 395a and 395b defines an adjustable spacing Δh along the build axis for receiving the solidification substrate laminate 298 (FIG. 16F). The latches 392a and 392b have a securing position and a releasing position. When the latches 392a and 392b are in a securing position, the adjustable spacing Δh is at a minimum to securely retain solidification substrate laminate 298 to solidification substrate laminate frame 388. When the

latches 392a and 392b are in a releasing position, the adjustable spacing Δh is at a maximum to allow the solidification substrate laminate 298 to be removed from or inserted into the solidification substrate laminate frame 388. Solidification substrate laminate stops 398a and 398b are connected to solidification substrate laminate frame member 391a and are spaced apart from one another along the x-axis to limit the y-axis movement of the solidification substrate laminate 298 as it is inserted along the y-axis from the solidification substrate laminate frame side 391b to the solidification substrate laminate frame side 391a. FIG. 16A shows the solidification substrate laminate 298 secured to solidification substrate laminate frame 388 (the laminate 298 is not shown in In FIGS. 16B and 16D). Latches 392a and 392b are in the secured position, in which the latches are oriented parallel to their respective frame side members 389a and 389b. To release the solidification substrate laminate 298 from the frame 388, the latches 392a and 392b are lifted into an orientation in which they are perpendicular to their respective frame members 389a and 389b. Thus, the rigid or semi-rigid solidification substrate laminate 298 may be removed from the solidification substrate laminate frame 388 while the frame 388 remains secured to the load frame 120. Thus, if necessary, the solidification substrate laminate 298 may be readily replaced by lifting latches 392a and 392b into the releasing configuration to increase the spacing Δh between the clamp lips 394a and 394b and their respective frame member bottom surfaces 395a and 395b.

[00200] In certain examples, and as shown in FIGS. 16E-16F, plungers 405a-405d are provided so that the upper surface of the rigid or semi-rigid solidification substrate 58 does not adhere to the underside of the solidification substrate laminate frame 388. A sealing member 400 may also be provided on the underside 397 of the frame 388 to prevent solidifiable material 50 from flowing between upper surface of the rigid or semi-rigid solidification substrate laminate 298 and the underside 397 of frame 388 into the inner portion of frame 388 between the sidewalls 389a, 389b, 391a, and 391b.

[00201] The solidification substrate laminate 298 is not shown in FIGS. 16D and 16E. As FIG. 16D indicates the solidification substrate laminate frame 388 and the laminate 298 can be removed as an integral unit from the solidification substrate assembly 57. However, in the

example of FIGS. 16A-16F, the laminate 298 can be removed from the assembly 57 without also removing the solidification substrate laminate frame 388.

[00202] The apparatus of FIGS. 16A-16E is designed for "right-side up" build processes such as the one depicted in FIGS. 1A-1E. In such processes, the volume of solidifiable material held in container 44 is typically much greater than in "upside down" build processes that use a shallow tray to hold the solidifiable material. In right-side up build processes, the larger volume of solidifiable material 50 creates larger pressure forces against the solidification substrate laminate 298 than would be the case if laminate 298 were used a part of a shallow tray in an upside down build process. For example, during a leveling operation, solidifiable material 50 will exert an upward (z-axis) force against the solidification substrate laminate 298. Once the laminate 298 is level, solidifiable material 50 will exert a dynamically varying pressure against the lower side of laminate 298 as solidifiable material 50 is squeezed out of the space between the exposed, upper object surface 82 and the laminate 298 (FIG. 1E). As explained previously, the actuator 66 may be operated to provide a level configuration force in the downward build (z) axis direction to resist the upward build (z) axis forces exerted by the solidifiable material 50 against the laminate 298. In certain examples, the ability to provide a level configuration force is particularly beneficial for ensuring that hydrodynamic transients in the solidifiable material 50 to not disturb the orientation of the laminate 298 relative to the x-y plane.

[00203] A solidification substrate assembly 57 with a solidification substrate laminate 298 used in lieu of film assembly 90 may be used in any of the apparatuses described herein, including those of FIGS. 6 and 10-13 in addition to the apparatus of FIGS. 4A-4E. As discussed previously, the use of a solidification substrate laminate 298 in place of a film assembly 90 can be beneficially used when solidifiable material 50 is brittle to prevent the breakage of fine structures, such as object supports. In preferred examples, solidification substrate assemblies 57 with solidification substrate laminate 298 are used when the solidifiable material (once solidified) has a percent elongation at break of greater than about three (3) percent, preferably greater than about five (5) percent, and even more preferably greater than about ten (10) percent. The term "percent elongation" refers to the elongation of a sample under a tensile load using the test procedure of ASTM D-638.

[00204] The apparatus of FIGS. 16A-16F and the solidification substrate laminates of FIGS. 17A-17C may be used with any of the methods of making a three-dimensional object from a solidifiable material described herein, including without limitation the methods of FIGS. 7, 8A-8B, and 15. Thus, the use of actuator 66 beneficially allows object peeling operations and leveling operations to be carried out with solidification substrate laminate 298 in right-side up build processes.

EXAMPLE 1

[00205] A 4 inch (x-axis) by 4 inch (y-axis) part is prepared using Envisiontec E-Denstone Peach on an apparatus that is configured similarly to the apparatus of FIGS. 4A-4E but for which the solidification substrate assembly 57 is not tilted. Peeling operations are carried out by moving the build platform 46 sufficiently downward to cause peeling and leveling (squeezing) operations are carried out by moving the build platform 46 upward to a distance of one layer thickness Δz from film 60. The object is built in 50 micron layers. Using the same materials and the dimensions, the object is also built on the apparatus of FIGS. 4A-4E with tilting. The time required to complete a squeezing operation (i.e., the time until the pressure measured by sensor 110 stabilizes at the reference value) is 45 seconds with the non-tilting implementation and 10 seconds with tilting. The full cycle for the solidification of a layer (including dropping the build platform, performing the "squeezing" or leveling operation, curing, and peeling) is 60 seconds for the non-tilting implementation and 12 seconds for the tilting implementation.

[00206] Referring to FIGS. 18-23C a portion of an apparatus for making a three-dimensional object is shown. Unless otherwise noted, like reference numerals refer to like parts in FIGS. 18-23C and the previous examples of FIGS. 1-2, 4A-6, and 10-13. The apparatus of FIGS. 18-23C comprises a solidification substrate assembly 457, a film assembly 90, a work table 64, and a load frame 120. Unlike the examples of FIGS. 1A-2, 4A-6, and 11-13, the solidification substrate assembly 457 (as the phrase is used herein) does not include the film assembly 90, linear solidification device 62, or the load frame 120. The solidification substrate frame 488, load frame 120, and film assembly 90 can be characterized as an "assembly" because they are interconnected (FIGS. 23A-23C). However, they do not automatically tilt together during the

formation of a three-dimensional object as in the case of FIGS. 1A-2, 4A-6, and 11-13. Instead, they are only tilted together manually during maintenance operations. The apparatus of FIGS. 18-23C is preferably used with solidifiable materials having a viscosity of at least about 200cp, and more preferably with photohardenable resins having a viscosity of at least about 200cp.

[00207] During the formation of three-dimensional object layers, there is a tendency to form a vacuum between the film 60 and rigid or semi-rigid solidification substrate 58. The apparatus of FIG. 18-23C provides a mechanism for breaking that vacuum before attempting to separate the exposed object layer 82 (FIGS. 1B-C) from film 60, which reduces the likelihood of damaging object 78 during the separation process. In the apparatus of FIGS. 18-23C, the rigid or semi-rigid solidification substrate 58 can be tilted away and separated from the upward facing surface of film 60 to break the vacuum before descending the build platform 46 to separate the part 78 from the film 60.

[00208] In the example of FIGS. 18-23C, the solidification substrate assembly 457 is tiltable relative to the film assembly 90 and load frame 120 about a tilting axis A_t (FIG. 20) that is parallel to the y-axis. Neither film assembly 90 nor load frame 120 are tiltable during an object manufacturing operation and are not operatively connected to the actuator shaft 68. Neither film assembly 90 nor load frame 120 tilt when actuator 66 receives an actuator activation signal from controller 184. However, they are manually tiltable about a secondary tilting axis B_t (FIG. 20) during maintenance operations along with the solidification substrate assembly 457 via hinges 74a and 74b, which connect the load frame 120 to the work table 64. Nor does the linear solidification device 62 or the linear slides 108a/108b along which it moves tilt with the solidification substrate assembly 457 in response to the extension or retraction of actuator shaft 68 in this example.

[00209] Solidification substrate assembly 457 comprises rigid or semi-rigid solidification substrate 58 which is transparent and/or translucent, as described previously. It also comprises solidification substrate frame 488 (best seen in FIG. 22). Solidification substrate frame 488 includes first and second side walls 532a and 532b which are spaced apart along the y-axis (i.e., the scanning axis of linear solidification device 62) and first and second cross-members 494c and 494d which are spaced apart along the x-axis (the travel axis of linear solidification device 62).

Cross member 494d sits above cross-member 497d along the build (z) axis, and cross-member 494c sits above cross-member 497c along the build (z) axis. Cross member 494c is integrally formed as a single component with latch plate 414. Knob 116 and shaft 122 are provided and operate as with the previous embodiments to selectively attach latch plate 414 to the distal end 70 of actuator shaft 68. As a result, when actuator shaft 68 extends or retracts along the build (z) axis, the solidification substrate frame 488 and solidification substrate 58 tilt about tilting axis A_t relative to load frame 120 and film assembly 90. In FIGS. 18-23C, the extension of actuator shaft 68 causes the solidification substrate 58 to tilt away from film 60 and build platform 46, while the retraction of actuator shaft 68 causes the solidification substrate 58 to tilt toward film 60 and build platform 46. However, the inverted actuator 166 of FIG. 6 may also be used. In that case, retraction of the actuator shaft would cause the solidification substrate 58 to tilt away from film 60 and build platform 46, and extension of the actuator shaft would cause the solidification substrate 58 to tilt toward film 60 and build platform 46.

[00210] In the example of FIGS. 18-23C, solidification substrate frame 488 is not directly attached to film assembly 90 in the manner shown in the previous examples. Instead, the film assembly 90 is attached to the load frame 120, and the solidification substrate frame 488 is hingedly attached to the load frame 120. As a result, when the actuator shaft 68 extends or retracts, it does not cause the film assembly 90 to tilt.

[00211] As best seen in FIGS. 20, 22, and 23C, hinges 504a and 504b are mounted on solidification substrate frame cross-member 494d and are spaced apart from one another along the y-axis. Hinges 504a and 504b are also mounted on respective adapter brackets 506a and 506b which are mounted on load frame 120. The hinges 504a and 504b allow the solidification substrate frame 488 to tilt about tiling axis A_t with respect to load frame 120 when actuator shaft 68 is extended or retracted along the build (z) axis.

[00212] The load frame 120 is connected to the film assembly 90 via fasteners 130a-130d (FIGS. 23A-B, fastener 130c is not visible) which engage corresponding openings (not shown) in the underside of load frame 120. As mentioned previously, the film assembly 90 is not directly attached to the solidification substrate frame 488 as is the case with the solidification substrate frame 88 shown in FIGS. 5A and 5B. Instead, the film assembly 90 is attached to the load frame

120, and the solidification substrate frame 488 is hingedly connected to the load frame 120 via hinges 504a/504b and adapter brackets 506a/506b. Thus, the solidification substrate frame 488 is tiltable relative to both load frame 120 and film assembly 90 about the tilt axis *At* defined by the hinges 504a and 504b. Because the actuator shaft 68 is selectively attachable to the solidification substrate frame latch plate 414, the extension or retraction of actuator shaft 68 along the build (z) axis causes the solidification substrate frame 488 and rigid or semi-rigid solidification substrate 58 to tilt about the tilting axis A_t relative to the load frame 120 and the film assembly 90. For ease of viewing, the load frame bracket 112 is not shown in FIGS. 23A-23C.

[00213] Linear solidification device 62 is slidably mounted on linear slides 108a and 108b which are spaced apart from one another along the y-axis. Pulleys 102a and 102b (not shown) are spaced apart from the motor shaft 100 along the x-axis and from one another along the y-axis. Respective timing belts 101a and 101b (not shown) are located in their respective housings 115a and 115b and are spaced apart from one another along the y-axis. The timing belts 101a and 101b engage the motor shaft 100 on one end and one of the two pulleys 102a and 102b on the other end. The pulleys 102a and 102b and timing belts are located in housings 115a and 115b, respectively.

[00214] The linear solidification device 62 is connected to each timing belt 101a and 101b. Thus, operation of motor 98 causes the shaft 100 to rotate about its longitudinal axis, which in turn causes the timing belts 101a and 101b to circulate. The circulation of the timing belts 101a and 101b traverses the linear solidification device 62 along the travel (x) axis with its attached linear bearings (not shown) slidably engaging the linear slides 108a and 108b (108b is not shown). Suitable configurations of a linear solidification device motor, pulleys, timing belts, and linear slides are provided in FIGS. 3-4 and 7-8 of Applicant's co-pending U.S. Patent Application No. 13/534,638 and the corresponding text at paragraphs 84-85 and 124-125, the contents of which are hereby incorporated by reference. In the example of FIGS. 4A-4E, linear slides 108a and 108b tilt along with the solidification substrate frame 88 and film assembly 90 in response to the extension or retraction of actuator shaft 68. However, in the example of FIGS. 18-23C, the linear slides 108a and 108b do not tilt in response to the extension or retraction of

actuator shaft 68. The linear slides 108a and 108b (along with timing belt housings 115a and 115b) are connected to load frame 120. Thus, when the load frame 120 is manually tilted with respect to work table 64 (via hinges 74a and 74b shown in FIG. 20), the linear slides 108, linear solidification device 62, housings 115a and 115b, timing belts 101a and 101b and pulleys 102a and 102b also tilt about secondary tilting axis B_t (FIG. 20). The hinges 504a and 504b and adapter brackets 506a and 506b are preferably designed to have a sufficient clearance relative to the work table 64 so that when the load frame 120, solidification substrate frame 488, housings 115a and 115b and linear solidification device 62 are manually tilted about secondary tilting axis B_t, neither the hinges 504a and 504b nor the adapter brackets 506a and 506b collide with the work table 64.

[00215] In certain examples, a clamp 502 (FIG. 21) is provided to restrain the movement of the load frame 120 and the film assembly frames 91 and 92 (FIGS. 5A and 5B) when the solidification substrate frame 488 is in a level configuration relative to the x-y plane. In certain examples, the movement of the build platform (not shown in FIGS. 18-23C) along the build (z) axis can cause hydrodynamic forces from the solidifiable material 50 to move the load frame 120 and/or the film assembly frames 91 and 92 along the build (z) axis, which can produce further hydrodynamic instability and increase the time required to build three-dimensional objects. In FIG. 21, load frame clamp 502 is depicted. Clamp 502 includes handle 512 which is connected to a vertically-oriented pivot member 510. Pivot member 510 is pivotably mounted within bracket 508 and is pivotable about pivot axis P defined by the point of connection of pivot member 510 and bracket 508. Pivot member 510 is connected to transverse member 506 to move the transverse member 506 along the build (z) axis.

[00216] Transverse member 506 has a stop surface 504 at its distal end. Stop surface 504 engages an upward (along the build (z) axis) facing surface of load frame bracket 112. When load frame clamp 502 is in a locked configuration (as shown in FIG. 21), the load frame bracket 112 is held in place between the load frame clamp stop surface 504 and the work table 64, thereby restraining the movement of the load frame 120 along the build (z) axis. Because the film assembly frames 91 and 92 are connected to the load frame 120, film assembly frames 91 and 92 are also restrained from moving along the build (z) axis. In other examples, a pressure or

force sensor such as sensor 110 (FIG. 12B) may be provided between work table 64 and bracket 112, and the clamp 502 may be adjustable to adjust the equilibrium force sensed by the pressure sensor 110. Pressure or force sensor 110 will sense the pressure applied by the solidifiable material 50 against the film assembly 90, solidification substrate frame 488, solidification substrate 58, and load frame 120 because the load frame 120 is hinged to work table 64 via hinges 74a and 74b. The pressure or force sensed by the pressure or force sensor 110 will be based on the difference between the upward force (along the build (z) axis) of the solidifiable material 50 and downward force (along the build (z) axis) of clamp 502, solidification substrate frame 488, solidification substrate 58, load frame 120, and film assembly 90. One advantage to using pressure or force sensor 110 is that the sensor 110 can be used to determine when excess solidifiable material has been squeezed out of the space between the exposed object surface 82 and the film 60. A controller (such as controller 184, FIG. 3) may be provided which compares the pressure or force sensed by sensor 110 to a pressure set point or which calculates the rate of change of the sensed pressure *dP/dt* (or *dF/dt* for the rate of change of the forced) and compares that value to a rate of change setpoint. Using the sensor 110 in either manner advantageously avoids the need for using leveling wait times to determine when to begin solidifying the next layer of solidifiable material (e.g., by traversing the linear solidification device 62 along the travel (x) axis and projecting solidification energy along the scanning (y) axis).

[00217] FIG. 18 shows the solidification substrate frame 488 in a level orientation relative to the x-y plane in which the actuator distal end 70 is in a fully retracted position. FIG. 19 shows the solidification substrate frame 488 in a tilted configuration. In the tilted configuration, the solidification substrate frame latch plate 414 is spaced apart from the upward facing surface of load frame side wall 95d by an actuator tilting distance Δa. In the example of FIGS. 18-23C, the distance Δa is not referred to as an actuator peeling distance because the tilting of the solidification substrate frame 488 does not peel the film 60 from the exposed surface of the three-dimensional object on the build platform (not shown in FIGS. 18-23C). Instead, the solidification substrate frame 488 and the solidification substrate 58 tilt relative to the load frame 120 and film assembly 90.

[00218] As discussed previously, in the example of FIGS. 18-23C, the linear solidification device 62, linear slides 108a and 108b, and the housings 115a and 115b do not tilt in response to the movement of actuator shaft 68. Thus, the linear solidification device 62 is preferably configured and operated to ensure that when the solidification substrate frame 488 tilts about tilting axis A_t, it does not collide with the linear solidification device 62. In the example of FIGS. 18-23C, prior to extending actuator shaft 68 along the build (z) axis, linear solidification device 62 is returned to a home position proximate motor shaft 100, as shown in FIG. 19. During a tilting operation, the home position is the position where the solidification substrate frame 488 is at its lowest position along the build (z) axis (because of the connection between hinges 504a and 504b). In contrast, the end of solidification substrate frame 488 that includes latch plate 414 is at its highest position along the build (z) axis during a tilting operation. Thus, by moving the linear solidification device 62 to the home position proximate the hinges 504a and 504b, a collision between the linear solidification device 62 and tilted solidification substrate frame 488 is avoided during tilting operations.

[00219] During an object layer solidification operation, linear solidification device 62 travels along the travel (x) axis and scans linear patterns of solidification energy along the scanning (y) axis based on object data representative of the three-dimensional object. In certain examples, the linear solidification device 62 scans solidification energy along the scanning (y) axis while traveling in both directions along the travel (x) axis. In other examples, the linear solidification device 62 scans solidification energy along the scanning (y) axis only while traveling along one direction along the travel (x) axis. When using the apparatus of FIGS. 18-23C, linear solidification device 62 preferably scans solidification energy along the scanning (y) axis only while moving from the side of the solidification substrate frame 488 on which latch plate 414 is located toward a home position proximate the side of the solidification substrate frame 488 on which the hinges 504a and 504b are located. Once the linear solidification device 62 reaches the home position, a first solidification substrate 58 tilting operation is commenced. An actuator activation signal is sent from controller 184 (FIG. 3) to actuator 66, causing the actuator shaft 68 to extend to an extended position (FIG. 19) along the build (z) axis. Unlike the first tilting operation used in the examples of FIGS. 1A-2, 4A-E, and 10-13, the first tilting operation used

with the example of FIGS. 18-23C is not used to peel the film 60 from the exposed object surface 82. Instead, it is used to separate the solidification substrate 58 from the film 60 (which may involve breaking a vacuum between substrate 58 and film 60) and to position the solidification substrate frame 488 and substrate 58 to perform a squeezing operation to squeeze excess solidifiable material from the space between the exposed object surface 82 and the film 60. Because the first tilting operation is not carried out to peel the object 78 from the film 60, the tilting distance (Δa) by which the actuator end 70 is extended need not be adjusted based on the area of the exposed object surface 82.

[00220] In preferred examples, during a first tilting operation, the actuator 66 is operated to move the actuator distal end 70 at a substantially constant velocity from a fully retracted position to a fully extended position to tilt the solidification substrate frame 488 and substrate 58 about the tilting axis A_t in a direction away from build platform 46 and the exposed object surface 82. Because the first tilting operation is not carried out to effect peeling, the velocity at which the actuator shaft 68 is extended need not be tailored to the area of the exposed object surface 82 or the solidifiable material.

[00221] The foregoing technique minimizes the likelihood of damaging the three-dimensional object 78 relative to other apparatuses. For example, when apparatuses such as those in FIGS. 1A-2, 4A-E and 10-13 are operated to peel the object 78 from the film 60 by tilting the solidification substrate assembly 57, vacuum forces may cause the film 60 to adhere to the substrate 58, which increases the force applied by the film 60 to the object 78 (because the film will not stretch or will only stretch to a limited degree even if it is otherwise resilient). The use of such tilting to peel the object 78 from the film 60 also creates shear forces in the object 78 which can damage the object 78. Even if the apparatuses of FIGS. 1A-2, 4A-E, and 10-13 are used with the solidification substrate assembly 57 locked in a level configuration, the film 60 may still adhere to the substrate 58 when the build platform 46 descends to peel the object 78 from the film 60. The strength of such forces will tend to damage the part and may limit the minimum surface area of parts that can reliably be built.

[00222] In contrast, when using the apparatus of FIGS. 18-23C, beneficially minimizes or reduces the creation of such shear forces since peeling is not carried out by tilting the film

assembly 90. In addition, any vacuum formed between film 60 and substrate 58 may be broken before peeling the object 78 from film 60 by tilting substrate 58 away from the film 60 before moving the build platform 46 downward along the build (z) axis to separate the object 78 from the film 60. This is particularly beneficial when parts with small surface areas are being formed (like small object supports) because the concentration of forces between the film 50 and the small surface area parts can become high enough to damage the supports when vacuum forces adhere the film 60 to the substrate 58.

[00223] Following the first tilting operation, the build platform 46 (FIG. 1) is moved downward along the build (z) axis and away from the solidification substrate 58 to separate the most recently formed object surface (e.g. surface 82 in FIGS. 1B-1D) from film 60. In certain examples, the distance the build platform 46 will move Δz_1 during an object separation operation will be greater than the next layer thickness Δz of solidifiable material used to form the three-dimensional object in order to facilitate separation of the exposed object surface 82 from film 60. In the same or other examples, the build platform 46 is moved downward at a constant speed during an object separation operation. The constant speed may be selected based on the particular solidifiable material and/or specific physical properties of the material, such as its viscosity.

[00224] After a waiting time ranging from about 0.1 to about 2 seconds, the build platform 46 (FIGS. 1A-2) is moved upward along the build (z) axis so that the exposed object surface 82 is one layer thickness Δz away from film assembly inner frame lower surface 93 (FIG. 23C) and film 60 (when film 60 is in a planar configuration). In certain examples, the upward movement of the build platform 46 may create hydrodynamic forces which cause part of film 60 to stretch or deflect upward away from the downward facing surface 93 of inner frame 92 due to the resilient nature of film 60. In certain examples, the build platform 46 is moved upward at a constant speed during this build platform upward movement operation.

[00225] Once the upward movement of build platform 46 is complete, a second tilting operation (which is a solidification substrate 58 leveling operation) is commenced in which the actuator shaft 68 is retracted to tilt the solidification substrate frame 488 and substrate 58 about tilt axis A_t in a direction toward build platform 46 and exposed object surface 82. The leveling

operation eventually restores the film 60 to a planar configuration and squeezes excess solidifiable material 50 (FIGS. 1A-2) from the space between film 60 and exposed object surface 82.

[00226] It has been found that carrying out a squeezing operation by tilting the solidification substrate 58 relative to film 60 reduces the likelihood of bubble formation in photocurable resin solidifiable materials. Such bubbles can result in distortions to the three-dimensional object 78. Such squeezing processes also expel trapped air between film 60 and substrate 58 more quickly and efficiently. In apparatuses in which no tilting is used or in which the solidification substrate 58 and film 60 tilt together, when the build platform 46 descends, air may be drawn into the space between the film 60 and the substrate 58. This air is undesirable and can distort the solidification energy that is transmitted through the substrate 58 and film 60 to the solidifiable material 50. As a result, after the build platform ascends to its final position for solidification of the next layer, solidification must be deferred until the air between film 60 and solidification substrate 58 is expelled, which prolongs object build times. It has been found that by tilting the solidification substrate 58 relative to and toward the film 60 prior to moving the build platform 46 upward to its final position, much or all of the air that would otherwise be trapped between the substrate 58 and film 60 is quickly expelled.

[00227] Following the leveling of the solidification substrate 58 and after the expiration of a leveling wait time, the linear solidification device 62 begins a layer solidification operation. In certain preferred examples, the leveling wait time is a fixed time based on the particular solidifiable material or its viscosity. In one example, a user enters an identifier indicative of the solidifiable material into a user interface of a user computer associated with the apparatus of FIGS. 18-23C, and set of computer executable instructions executed by processor 188 (FIG. 3) retrieves a leveling wait time from tilting parameter database 196. The tilting parameter database 196 stores leveling wait times in association with corresponding solidifiable material identifier data. Once the leveling wait time expires, solidification of the next object layer begins. In examples using linear solidification device 62, at the expiration of the leveling wait time, the linear solidification device 62 will being traveling along the travel (x) axis and selectively scanning solidification energy along the scanning (y) axis to solidify the solidifiable material.

[00228] In certain examples, it is preferable to use a leveling wait time that is greater for an initial set of object layers and which is lower for the remaining object layers. In general, the larger the area of exposed object surface 82 is, the longer the leveling wait time will be in order to achieve a stable, desired thickness Δz of the solidifiable material. Earlier in the object build, the entire area of the build platform 46 is close to the film 60 and will affect the required leveling time. Thus, in certain examples, the leveling wait time for an initial set of layers is at least about 1.5, preferably at least about 2.0, and more preferably, at least about 3.5 times the leveling wait time for the subsequent layers. At the same time, the leveling wait time for the initial set of layers is no more than about 10, preferably no more than about 6, and still more preferably no more than about 4.5 times the leveling time for the subsequent layers. The initial set of layers is preferably at least about 5, more preferably at least about 10, and still more preferably at least about 15 layers. At the same time, the initial set of layer is preferably no more than about 40, more preferably no more than about 30, and still more preferably not more than about 25 layers.

[00229] In another example, correlations between the leveling wait time and the area of the exposed object surface 82 (i.e., the surface area of the most recently solidified object layer) may be stored in a database such as tilting parameter database 196, with the particular correlations being stored in association with solidifiable material identifier data or viscosity data. In accordance with such examples, the appropriate correlation is selected based on the particular solidifiable material being used (which may be indicated by a user entry in a suitable user interface). For each leveling operation, the area of the exposed object surface 82 (i.e., the area of the upward facing surface of the most recently solidified object layer) may be calculated for each layer. The correlation of leveling wait time versus exposed object surface area may be used to determine the leveling wait time for that layer. In such cases, the leveling wait time will be dynamic throughout the object build and will vary with the surface area of the most recently formed object layer. Even when such correlations are used, for an initial set of layers (as described above), it may be desirable to use the entire build platform area with the correlation to select the desired leveling wait time because the entire build platform area may be determinative of when the squeezing of excess material is complete for the early part of an object build process.

[00230] In other examples, it may be desirable to avoid using leveling wait times to determine when to begin the next object layer solidification operation. Pressure or force sensor 110 may be provided. In certain implementations, a comparison of the pressure or force sensor 110 reading and a selected set point may be used to determine when the squeezing of excess material is complete and the next object layer solidification operation can begin. In other examples, the readings from sensor 110 may be converted to the rate of change of the pressure with respect to time *dP/dt* (or *dF/dt* for a force rate of change) and the measured rate of change may be compared to a set point to determine when squeezing is complete. The use of a sensor avoids the need to provide fixed leveling times or correlations of leveling time versus the surface area of the last exposed object surface.

[00231] Referring to FIG. 24, a method of forming a three-dimensional object using a rigid or semi-rigid solidification substrate 58 that is transparent and/or translucent and which tilts relative to a film is described. The method may be used with the apparatus of FIGS. 18-23C or other apparatuses that are configured to carry out the specified steps even if the apparatus does not have the same structure as that of FIGS. 18-23C. In accordance with the method, object data that defines the dimensions and shape of the three-dimensional object 78 (FIG. 2) is read in step 1120. Although not depicted, a step may be included wherein a user identifies the solidifiable material being used (e.g., by making a selection on a touch screen that provides solidifiable material identity information). That selection may then be used to select one or more tilting parameters from a tilting parameter database 196 (FIG. 3). In preferred examples, the one or more tilting parameters include a leveling wait time.

[00232] The layer index *k* is initialized in step 1122 and is incremented in step 1124. In step 1126, portions *P* of the solidifiable material 50 are solidified at locations in the *x, y* plane which correspond to the current value of the layer index *k*. If digital light projector (DLP) or spatial light modulator (SLM) type of solidification device is used, the entire layer will be exposed to solidification energy at once in steps 1126 and 1128. However, if a linear solidification device such as device 62 is used, in step 1126 controller 184 activates motor 98 to rotate shaft 100. As shaft 100 rotates about its longitudinal axis, linear solidification device 62 travels along the travel (x) axis starting from a position proximate the latch plate 414 towards a position proximate

hinges 504a and 504b. At a plurality of locations along the travel (x) axis, solidification energy is scanned along the scanning (y) axis as the linear solidification device 62 moves along the travel (x) axis. In certain examples, the linear solidification device 62 includes a rotating polygonal mirror that acts as a linear scanning device, and the controller 184 (FIG. 3) activates the linear scanning device. In addition, the controller 184 selectively activates a solidification energy source that comprises part of the linear solidification device 62 to selectively project solidification energy toward the linear scanning device which then deflects the solidification energy onto the solidifiable material in linear patterns. The selective activation of the solidification energy source and the rotation of the polygonal mirror dictate the pattern of the various linear scans of solidification energy along the scanning (y) axis.

[00233] In step 1128 a determination is made as to whether solidification is complete for the current layer. If it is not, control transfers to step 1126 and solidification of the layer continues. Otherwise, control transfers to step 1130.

[00234] In step 1130 a first tilting operation is commenced. In the example of FIGS. 18-23C, controller 184 (FIG. 3) issues an actuator activation signal that causes the actuator shaft 68 to extend from the retracted position of FIG. 18, thereby causing the solidification substrate frame 488 and substrate 58 to tilt away from build platform 46 and exposed object surface 82 about tilting axis A_t relative to the film assembly 90 and load frame 120. If the inverted actuator 166 of FIG. 6 is used, the actuator activation signal will cause the actuator shaft 166 to retract to cause the solidification substrate 58 to tilt relative to the film 60. The speed at which the actuator shaft 68 extends is preferably constant and may be independent of both the solidifiable material and the area of exposed object surface 82 because the tilting operation is not being used to peel film 60 from object 78. If a vacuum was formed between the film 60 and substrate 58, the first tilting operation will break it.

[00235] In step 1132 an object separation operation is carried out to separate object 78 from film 60. Step 1132 is preferably carried out by moving a build platform away from a rigid or semi-rigid solidification substrate. In the case of the apparatus of FIGS. 18-23C, the object separation operation of step 1132 is carried out by moving the build platform 46 vertically downward to separate the exposed object surface 82 from the film 60. The build platform 46 is

preferably moved down by distance Δz_1 which is greater than the thickness Δz of the next object layer to be solidified. Moving the build platform by a distance Δz_1 greater than Δz better ensures that sufficient solidifiable material will be available to form the next layer in a reasonable amount of time. In certain examples, the build platform 46 is moved downward at a constant speed that is selected to avoid damaging the partially-formed three-dimensional object 78. In other examples, the speed may be adjusted based on considerations that include the particular solidifiable material being used and/or the area of the exposed object surface.

[00236] When step 1132 is complete, the exposed object surface 82 has separated from the film 60. In step 1134 the current value of the layer index k is compared to the maximum index value k_{max}. If the current layer index value has reached the maximum value, the object build is complete, and the method ends. Otherwise, control proceeds to step 1136.

[00237] In step 1136 the controller 184 energizes a build platform motor to cause build platform 46 to move upward along the build (z) axis by a distance Δz_2. The distance Δz_2 is selected to that the exposed object surface 82 is spaced apart from the downward-facing surface 93 of inner film assembly frame 92 by an amount equal to the desired thickness of the next layer Δz. The magnitude of the distance Δz_2 will equal the magnitude of the distance Δz_1 by which the build platform 46 was moved downward in step 1130 less the desired layer thickness Δz. The upward movement of the build platform 46 may create hydrodynamic forces that cause the film 60 to stretch upward along the build (z) axis in step 1136.

[00238] In step 1138 a second tilting operation that comprises a solidification substrate leveling operation is carried out. The controller 184 issues an actuator activation signal that causes the actuator shaft 68 to retract along the build (z) axis from the extended position of FIG. 19 to the retracted position of FIG. 18. If the inverted actuator 166 of FIG. 6 is used, the actuator activation signal will cause the actuator shaft 166 to extend relative to housing 169 to cause the solidification substrate 58 to tilt toward film 60 and build platform 68. In certain preferred examples, the leveling velocity (i.e., the velocity at which the actuator shaft distal end 70 is retracted) is constant and is independent of the solidifiable material or the area of exposed object surface 82. Step 1138 causes excess solidifiable material 50 located between film 60 and exposed object surface 82 to be squeezed out from the space between the exposed object surface

82 and film 60. Step 1138 also preferably removes bubbles that may have formed in the solidifiable material 50. In addition, step 1138 also preferably expels air from between the film 60 and substrate 58. As explained previously, such trapped air can distort the solidification energy transmitted through the substrate 58 and film 60, and as a result, the second tilting operation reduces the waiting time required before solidifying the next object layer.

[00239] The solidification of the next layer of solidifiable material 50 is preferably deferred until the solidifiable material 50 reaches an equilibrium condition. If a pressure sensor is not used (step 1140), then solidification of the next layer is deferred until the expiration of a leveling wait time (step 1142). In certain examples, the leveling wait time is a fixed time selected based on the particular solidifiable material being used and/or a particular physical property of that material, preferably, its viscosity. In certain implementations, a user identifies the material by inputting its name into a user interface, and the corresponding leveling time is retrieved from a database that relates material names to leveling times. In other implementations, the user inputs a viscosity into a user interface, and the corresponding leveling time is retrieved from a database that relates viscosities to leveling times.

[00240] It is preferred to use longer leveling wait times during the solidification of an initial set of object layers. In general, the leveling wait time is selected to ensure that any excess material between the exposed surface of the last formed object layer 82 and the film 60 is squeezed out before solidifying the next object layer. However, during the formation of an initial set of object layers, the time required to complete squeezing is more strongly dependent on the surface area of the entire build platform 46 than of the most recently formed object layer because the platform 46 is so close to the solidification substrate 58. In those examples, in which fixed leveling times are selected based on the identity of the solidifiable material or a particular physical property (e.g., viscosity) thereof, the leveling wait time for the initial set of layers is at least about 1.5, preferably at least about 2.0, and more preferably, at least about 3.5 times the leveling time for the subsequent layers. At the same time, the leveling time for the initial set of layers is no more than about 10, preferably no more than about 6, and still more preferably no more than about 4.5 times the leveling time for the subsequent layers. The initial set of layers is preferably at least about 5, more preferably at least about 10, and still more preferably at least

about 15 layers. At the same time, the initial set of layer is preferably no more than about 40, more preferably no more than about 30, and still more preferably not more than about 25 layers.

[00241] Step 1142 may also be carried out by using a correlation between the area of the exposed surface 82 of the most recently formed object layer and leveling time. A variety of such correlations may be provided, wherein each correlation corresponds to a particular solidifiable material and/or a particular physical property thereof (e.g., viscosity). After each layer is formed, the area of the exposed object surface 82 is calculated and then used as an input to the correlation to retrieve the leveling wait time. Even when such correlations are used, however, for an initial set of layers, it may be desirable to use a longer leveling wait time that is based on the entire surface area of build platform 46 because that area will tend to have a greater influence on when the squeezing of excess material is complete for the initial set of layers as opposed to subsequent layers.

[00242] If a pressure or force sensor is present in step 1040 (i.e., a sensor such as sensor 110 which is directly or indirectly indicative of the force or pressure applied by the solidifiable material 50 against the film 60), the sensor readings may be used to determine when to begin solidifying the next object layer instead of using static or dynamic leveling wait times. In one example, a controller is provided with a selected sensor setpoint, and once the sensor reading reaches the setpoint, the solidification of the next object layer is commenced. In another example, the readings from the sensor are converted to rate of change values (*dP/dt* for pressure and *dF/dt* for force) and compared to a selected rate of change setpoint such that when the measured rate of change value reaches the setpoint, solidification of the next object layer begins.

[00243] To further minimize bubble formation within the solidifiable material, the film 60 is preferably held at a level within solidifiable material 50 that is below the exposed surface of the film 60 in the x-y region outside of the film. In certain examples, the distance of the film 60 below the exposed solidifiable material surface is no less than about 1 mm, preferably no less than about 2 mm, and still more preferably no less than about 3 mm. In the same or other examples, the distance is preferably no greater than about 6mm, more preferably no greater than 5mm, and still more preferably no greater than about 4mm.

EXAMPLE 2

[00244] Six (6) full solid dental arches with a bottom palate are made using the apparatus of FIGS. 18-23C. The build envelope is approximately 10 inches by 6 inches (254mm x 152.4mm). The arches are distributed evenly throughout the build envelope. The solidification substrate 88 is a transparent and translucent glass having a length (x-axis) of 11 inches and a width (y-axis) of 7 inches (279.4 mm x 177.8 mm). The maximum x-y area of each arch is about 9 inches by 9 inches (229 mm x 229 mm). The solidifiable material is a UV-curable, nanofilled material called E-Appliance, which is supplied by Envisiontec, Inc. of Dearborn Heights, Michigan. The six (6) dental arches are built in layers of solidifiable material having a layer thickness (Δz) of 75 microns (0.075mm).

[00245] Following the solidification of each of the first twenty (20) layers of the dental arches, a first tilting operation is carried out. The actuator shaft 68 is extended such that its distal end 70 travels a distance Δa of one inch (25.4mm) in one second, causing the solidification substrate to tilt relative to film 60 and load frame 120 about tilting axis A_t. As explained previously, this step breaks any vacuum formed between the film 60 and substrate 58.

[00246] Following the first tilting operation, the build platform 46 descends along the build (z) axis at a rate of about 2500 microns/second (2.5 mm/sec) to a distance of about 15000 microns (15mm). After a fixed waiting time that ranges between 0.1 to 2 seconds, the build platform 46 then ascends at a speed of about 20,000 microns/second (20 mm/sec) to a distance that positions the build platform 46 one layer thickness (75 microns or 0.075mm) below its location before it descended.

[00247] After the build platform 46 has ascended to a position that is one layer thickness below its starting point, a second tilting operation (a solidification substrate leveling operation) is commenced. The shaft 68 is retracted such that its distal end 70 travels one inch in one second to tilt the solidification substrate frame 488 and substrate 58 into a level condition. A six (6) second leveling waiting period is then commenced prior to beginning an object layer solidification operation with linear solidification device 62.

[00248] For the layers after the first twenty (20) layers of the dental arches, after each layer is solidified, a first tilting operation is commenced using the same procedure as for the first twenty

(20) layers. The build platform 46 then descends at a speed of about 10,000 microns/sec (10 mm/sec) to a distance of about 15000 microns (15mm). Following the expiration of the same fixed waiting period used for the first 20 layers, the build platform 46 ascends at a speed of about 20,000 microns/second (20 mm/sec) to a distance that positions the build platform 46 one layer thickness (75 microns or 0.075mm) below its location before it descended.

[00249] For the layers after the first twenty (20) layers, after the build platform 46 has ascended to a position that is one layer thickness below its starting point, a second tilting operation (leveling operation) is carried out by retracting shaft 68 such that its distal end 70 travels one inch in one second to tilt the solidification substrate frame 488 and substrate 58 into a level condition. A six (6) second waiting period is then commenced prior to beginning an object layer solidification operation with linear solidification device 62. A 25 mm height (along the build (z) axis) of the set of six (6) dental arches is completed in 2.25 hours.

COMPARATIVE EXAMPLE

[00250] Six (6) full solid dental arches with a bottom palate are made using the apparatus of FIG. 4B. The build envelope is approximately 10 inches by 6 inches (254mm x 152.4mm). The arches are distributed evenly throughout the build envelope. The solidification substrate 88 is glass having a length (x-axis) of 11 inches and a width (y-axis) of 7 inches (279.4 mm x 177.8 mm). The maximum x-y area of each arch is about 9 inches by 9 inches (229 mm x 229 mm). The arches have the same dimensions and are positioned in the same manner as in Example 2. The same solidifiable material is used as in Example 2.

[00251] The solidification substrate assembly 57 is not tilted to peel the object from the film 60. Instead, the assembly 57 remains locked in a level configuration during the formation of the object.

[00252] Following the solidification of each of the first twenty (20) layers of the dental arches, after each layer is solidified the build platform 46 descends along the build (z) axis at a rate of about 2500 microns per second (2.5 mm/sec) to a distance ranging from about 10,000 microns (10 mm) to about 12,500 microns (12.5 mm). After a fixed period of time that ranges from 0.1 to 2 seconds (but which is the same as the fixed waiting period used in Example 2), the

build platform 46 then ascends along the build (z) axis at a rate of about 5000 microns/second (5 mm/sec) by a distance that positions the build platform one layer thickness (75 microns or 0.075 mm) below its location before it descended.

[00253] After the build platform 46 has ascended to the position that is one layer thickness below its starting point, a waiting period is commenced prior to beginning an object layer solidification operation with linear solidification device 62. For the first 20 layers of the object build, the waiting time is 40 seconds.

[00254] For the layers beyond the first 20 layers, following the solidification of each layer, the build platform 46 descends along the build (z) axis at a rate of about 5000 microns/second (5 mm/sec) to a distance of about 10000 microns (10 mm). The build platform 46 then ascends at a rate of about 7500 microns/second (7.5 mm/sec) to a distance that positions the build platform one layer thickness (75 microns or 0.075mm) below its location before it descended.

[00255] After the build platform 46 has ascended to the position that is one layer thickness below its starting point, a waiting period is commenced prior to beginning an object layer solidification operation with linear solidification device 62. For the layers following the first 20 layers, the waiting time is about 10 seconds. The waiting time is longer for the first 20 layers to ensure that a sufficient amount of material is provided to solidify the next layer. An object height of 25 mm is completed in about 3 hours.

[00256] As Example 2 and the Comparative Example indicate, by using the apparatus of FIGS. 18-23C, the time required to build a 25 mm height of the same set of dental arches of the same build quality was reduced by three-quarters of an hour. The reduction of build time is believed to be attributable to several factors. First, the vacuum between the film and the solidification substrate is broken before peeling the object from the film, which allows the build platform to descend at a greater speed to effect object peeling without risking damage to the object.

[00257] In addition, the use of a solidification substrate 58 that tilts relative to a film 60 provides an expedient means of expelling air from between the solidification substrate 58 and the film 60. In the Comparative Example, air pockets tend to form in this location, and the waiting time before commencing an object layer solidification operation must be increased to allow the

air to be removed. Otherwise, the air pockets can defocus the solidification energy and cause distortions in the three-dimensional object 78. Thus, the leveling wait times used in Example 2 are significantly lower than in the Comparative Example.

[00258] Also, in Example 2, the build platform 46 ascends at a point in time at which the solidification substrate is tilted away from film 60, which allows film 60 to stretch. This allows the speed at which the build platform ascends to be increased, at least in part, because the pressure forces in the solidifiable material are not as great and are less likely to damage the object 78.

[00259] In addition, in Example 2 the squeezing out of excess solidifiable material from between the solidification substrate 58 and the film 60 is carried out by tilting the solidification substrate 58 relative to the film. In the Comparative Example, the squeezing out is carried out by the upward, vertical movement of the build platform. The film 60 remains flush against the solidification substrate 60 during the squeezing process. In contrast, in Example 2 the film 60 stretches upward along the build (z) axis after the build platform 46 ascends, and the squeezing is caused by the force of the solidification substrate 58 against the film 60 as the solidification substrate 58 tilts. The use of a tilting operation to effect squeezing is believed to expedite the squeezing process.

CLAIMS

What is claimed is:

1. An apparatus for making a three-dimensional object from a solidifiable material, comprising:

a build platform movable along a first axis;

a solidification energy source;

a film assembly;

a solidification substrate assembly comprising a rigid or semi-rigid solidification substrate that is transparent and/or translucent;

an actuator operatively connected to the solidification substrate assembly; and

at least one controller operatively connected to the actuator, wherein the at least one controller comprises a processor and a non-transitory computer readable medium having computer executable instructions stored thereon, and when the computer executable instructions are executed by the processor, the at least one controller generates an actuator activation signal;

wherein the film assembly includes at least one frame, and a film disposed in the at least one frame, the solidification substrate is located between the solidification energy source and the film along the first axis, and the solidification substrate assembly is tiltable relative to the film assembly about a second axis perpendicular to the first axis when the actuator receives the actuator activation signal.

2. The apparatus of claim 1, wherein the solidifiable material has a viscosity at 25°C that is at least about 200 cP.

3. An apparatus according to claim 1 or claim 2, wherein the solidification energy source is movable along a third axis perpendicular to the first axis and the second axis.

4. An apparatus according to any of claims 1-3, wherein the film is located between the build platform and the solidification energy source along the first axis.

5. An apparatus according to any of claims 1-4, further comprising a load frame, wherein the rigid or semi-rigid solidification substrate is disposed in a substrate frame, and the substrate frame is hingedly connected to the load frame.

6. The apparatus of claim 5, further comprising a work table, wherein the load frame is connected to the work table, and the at least one frame of the film assembly is connected to the load frame.

7. An apparatus according to claim 5 or claim 6, wherein the substrate frame is hingedly connected to the load frame at a first substrate frame location, the actuator is connected to the substrate frame at a second substrate frame location, and the first substrate frame location and the second substrate frame location are spaced apart along a third axis.

8. An apparatus according to any of claims 1-7, wherein the actuator has a shaft with a distal end that is operatively connected to the solidification substrate assembly, the actuator shaft is extendable to a first position along the first axis and retractable to a second position along the first axis to tilt the solidification substrate assembly about the second axis.

9. An apparatus according to any of claims 1-8, wherein the actuator is a pneumatic actuator.

10. An apparatus according to any of claims 1-9, wherein the second axis is spaced apart from the film assembly in a direction along a third axis.

11. The apparatus of claim 8, wherein the actuator activation signal causes the actuator shaft distal end to extend from the second position to the first position after solidifying a layer of the solidifiable material and prior to solidifying a next layer of the solidifiable material.

12. The apparatus of claim 11, wherein the actuator activation signal causes the actuator shaft distal end to extend from the second position to the first position before the build platform moves away from the solidification substrate assembly along the first axis.

13. The apparatus of claim 8, wherein the actuator activation signal causes the actuator shaft distal end to retract from the first position to the second position after solidifying a layer of the solidifiable material and prior to solidifying a next layer of the solidifiable material.

14. The apparatus of claim 13, wherein the actuator activation signal causes the actuator shaft distal end to retract from the second position to the first position before the build platform moves away from the solidification substrate assembly along the build axis.

15. An apparatus according to any of claims 1-7, wherein the actuator has a proximal end that is operatively connected to the solidification substrate assembly, and the actuator proximal end is extendable to a first position along the first axis and retractable to a second position along the first axis to tilt the solidification substrate assembly about the second axis.

16. The apparatus of claim 15, wherein the actuator activation signal causes the actuator proximal end to extend from the second position to the first position after solidifying a layer of the solidifiable material and prior to solidifying a next layer of the solidifiable material.

17. The apparatus of claim 16, wherein the actuator activation signal causes the actuator proximal end to extend from the first position to the second position before the build platform moves away from the solidification substrate assembly along the build axis.

18. An apparatus according to any of claims 1-17, further comprising a tilting parameter database, wherein the tilting parameter database comprises a plurality of solidifiable material identifiers and a plurality of sets of tilting parameters, each solidifiable material identifier is associated with a set of tilting parameters from the plurality of sets of tilting parameters, and each set of tilting parameters comprises at least one tilting parameter.

19. The apparatus of claim 18, wherein the at least one tilting parameter is selected from the group consisting of an actuator tilting distance, a build platform velocity, and an actuator velocity.

20. An apparatus according to any of claims 1-19, wherein the at least one controller is operatively connected to the solidification energy source, and when the computer executable instructions are executed by the processor, the at least one controller generates a plurality of solidification energy signals that selectively activate the solidification energy source to solidify a layer of the solidifiable material in a pattern corresponding to the three-dimensional object, and the at least one controller generates the actuator activation signal after the cessation of a final solidification energy signal for the layer and before the generation of an initial solidification energy signal for a next layer.

21. An apparatus according to any of claims 1-20, wherein the actuator activation signal causes the actuator to tilt the solidification substrate assembly about the second axis in a direction away from the build platform.

22. The apparatus of claim 21, wherein the actuator activation signal is a first actuator activation signal, and when the computer executable instructions are executed by the processor, the at least one controller generates a second actuator activation signal that causes the actuator to tilt the solidification substrate assembly about the second axis in a direction toward the build platform.

23. An apparatus according to any of claims 1-22, wherein the actuator has one selected from a distal shaft end with an end of travel location along the first axis and a proximal housing end with an end of travel along the proximal axis, the apparatus further comprises a switch positioned to generate an end of travel signal when the one selected from the actuator distal shaft end and the actuator proximal housing end reaches the end of travel location, the switch is connected to the at least one controller, and when the computer executable instructions are executed by the processor, the at least one controller generates the actuator activation signal in response to receiving the end of travel signal.

24. An apparatus according to any of claims 1-20, wherein the actuator activation signal causes the actuator to tilt the solidification substrate assembly about the second axis in a direction toward the build platform.

25. An apparatus according to any of claims 1-24, further comprising a solidifiable material container having a closed bottom, an open top, and a volume of the solidifiable material, wherein the at least one frame in the film assembly is located at a first distance from the bottom of the solidifiable material container, and the solidifiable material has an exposed surface spaced apart from the bottom of the solidifiable material container by a second distance along the first axis, and the second distance is greater than the first distance.

26. An apparatus according to any of claims 1-25, further comprising a sensor configured to provide a value indicative of a force or a pressure applied by the solidifiable material to the film.

27. An apparatus according to any of claims 1-26, further comprising a database, wherein the database comprises a plurality of solidifiable material identifiers and a plurality of leveling wait times, and each solidifiable material identifier in the plurality of solidifiable material identifiers corresponds to a leveling wait time in the plurality of leveling wait times, and the computer readable medium has computer executable instructions stored thereon which, when executed by the processor, select a leveling wait time from among the plurality of leveling wait times based on a user-input solidifiable material identifier.

28. An apparatus according to any of claims 1-26, further comprising a database, where in the database comprises a plurality of solidifiable material identifiers and a plurality of correlations between leveling wait times and surface areas for a most recently formed object layer, each solidifiable material identifier in the plurality of solidifiable material identifiers corresponds to a correlation from among the plurality of correlations, and the computer readable medium has computer executable instructions stored thereon which, when executed by the processor, calculate a surface area of a most recently formed object layer, select a correlation from among the plurality of correlations based on a user-input solidifiable material identifier, and determine a leveling wait time from the selected correlation based on the calculated surface area of the most recently formed object layer.

29. A method of making a three-dimensional object from a solidifiable material, comprising:

solidifying a first layer of the solidifiable material in a first pattern corresponding to a first portion of the three-dimensional object to form a first solidified exposed object surface in contact with a film disposed between the first layer of the solidifiable material and a rigid or semi-rigid solidification substrate that is transparent and/or translucent, wherein the first layer of the solidifiable material is located between a build platform and the film along a build axis;

first tilting the rigid or semi-rigid solidification substrate relative to the film about a tilting axis in a direction away from the build platform to separate the solidification substrate from the film;

moving the build platform away from the rigid or semi-rigid solidification substrate, thereby separating the film from the first solidified exposed object surface;

providing a second layer of the solidifiable material between the first solidified exposed object surface and the film;

second tilting the solidification substrate relative to the film about the tilting axis in a direction toward the build platform; and

solidifying the second layer of the solidifiable material in a second pattern corresponding to a second portion of the three-dimensional object.

30. The method of claim 29, wherein the step of providing a second layer of the solidifiable material between the first solidified exposed object surface and the film comprises moving the build platform toward the film.

31. The method of claim 30, wherein the step of moving the build platform toward the film is carried out before the step of second tilting the solidification substrate relative to the film about the tiling axis in a direction toward the build platform.

32. The method of claim 29, further comprising providing an actuator operatively connected to the solidification substrate, wherein the actuator has an extended configuration and a retracted

configuration, and the step of first tilting the solidification substrate about the tilting axis comprises adjusting the actuator from the retracted configuration to the extended configuration.

33. The method of claim 29, further comprising providing an actuator operatively connected to the solidification substrate, wherein the actuator has an extended configuration and a retracted configuration, and the step of second tilting the solidification substrate about the tilting axis comprises adjusting the actuator from the extended configuration to the retracted configuration.

34. The method of claim 29, further comprising providing an actuator operatively connected to the solidification substrate, wherein the actuator has an extended configuration and a retracted configuration, and the step of first tilting the solidification substrate about the tilting axis comprises adjusting the actuator from the extended configuration to the retracted configuration.

35. The method of claim 29, further comprising providing an actuator operatively connected to the solidification substrate, wherein the actuator has an extended configuration and a retracted configuration, and the step of second tilting the solidification substrate about the tilting axis comprises adjusting the actuator from the retracted configuration to the extended configuration.

36. A method according to any of claims 29-35, further comprising the step of waiting until the expiration of a leveling wait time after completing the step of second tilting the solidification substrate relative to the film about the tilting axis in a direction toward the build platform and before the step of solidifying the second layer of the solidifiable material in a second pattern corresponding to a second portion of the three-dimensional object.

37. The method of claim 36, further comprising the step of selecting the leveling wait time based on the identity of the solidifiable material.

38. The method of claim 36, further comprising the step of selecting the leveling wait time based on the viscosity of the solidifiable material.

39. The method of claim 36, further comprising the step of calculating the surface area of a most recently formed layer of the three-dimensional object, and selecting the leveling wait time

based on a selected correlation between leveling wait times and surface areas of most recently formed object layers.

40. The method of claim 39, further comprising selecting a correlation between leveling wait times and surface areas of most recently formed object layers from among a plurality of correlations between leveling wait times and surface areas of most recently formed object layers based on the identity of the solidifiable material.

41. The method of claim 39, further comprising selecting a correlation between leveling wait times and surface areas of most recently formed object layers from among a plurality of correlations between leveling wait time and surface areas of most recently formed object layers based on the viscosity of the solidifiable material

42. The method of claim 29 further comprising the step of waiting until a pressure or force sensor measurement value reaches a setpoint value after completing the step of second tilting the solidification substrate relative to the film about the tilting axis in a direction toward the build platform and before the step of solidifying the second layer of the solidifiable material in a second pattern corresponding to a second portion of the three-dimensional object.

43. The method of claim 29 further comprising the step of waiting until a pressure or force rate of change value reaches a setpoint value after completing the step of second tilting the solidification substrate relative to the film about the tilting axis in a direction toward the build platform and before the step of solidifying the second layer of the solidifiable material in a second pattern corresponding to a second portion of the three-dimensional object.

44. A method according to any of claims 29-43, further comprising the step of providing a volume of the solidifiable material having an exposed surface and locating the film beneath the exposed surface.

45. A method according to any of claims 29-44, wherein the step of first tilting the rigid or semi-rigid solidification substrate relative to the film about a tilting axis in a direction away from

the build platform is carried out before the step of moving the build platform away from the rigid or semi-rigid solidification substrate.

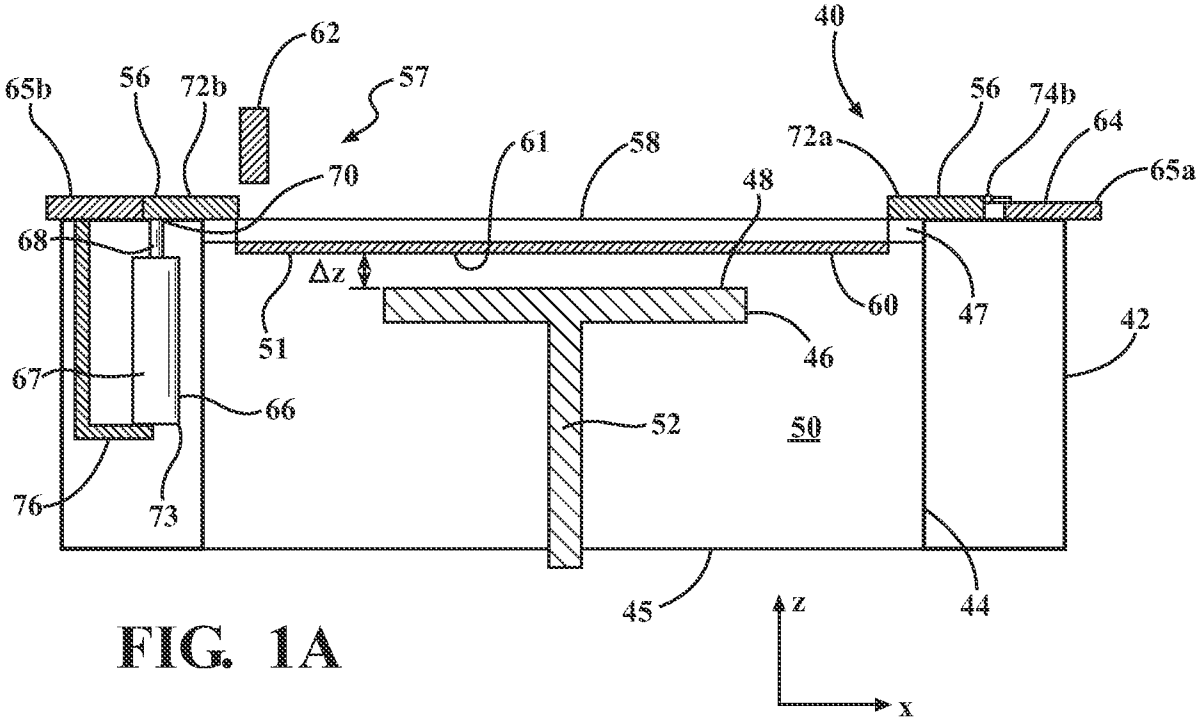

62
40
65b
56
72b
57
56
74b
64
61
58
72a
65a
70
48
68
Δz
60
47
51
46
42
67
66
52
50
76
73
45
44
z
x

FIG. 1A

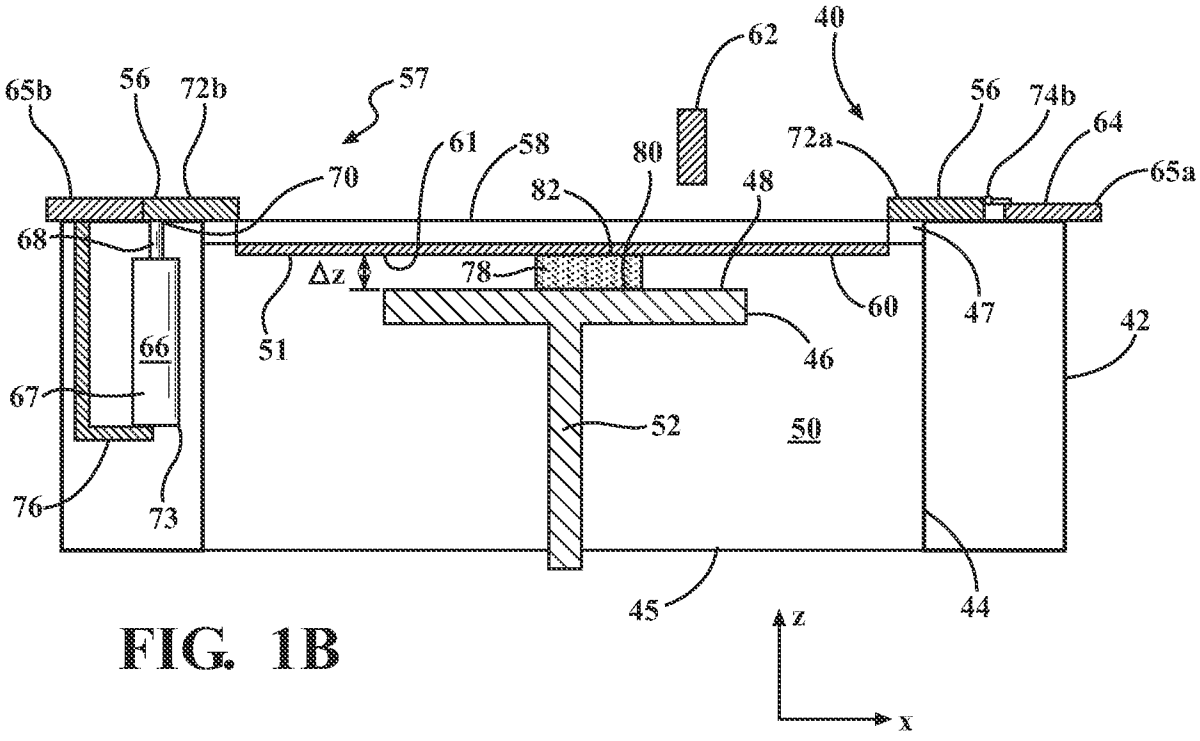

62
40
65b
56
72b
57
56
74b
64
61
58
80
72a
65a
70
82
48
68
Δz
78
60
47
66
51
46
42
67
52
50
76
73
45
44
z
x

FIG. 1B

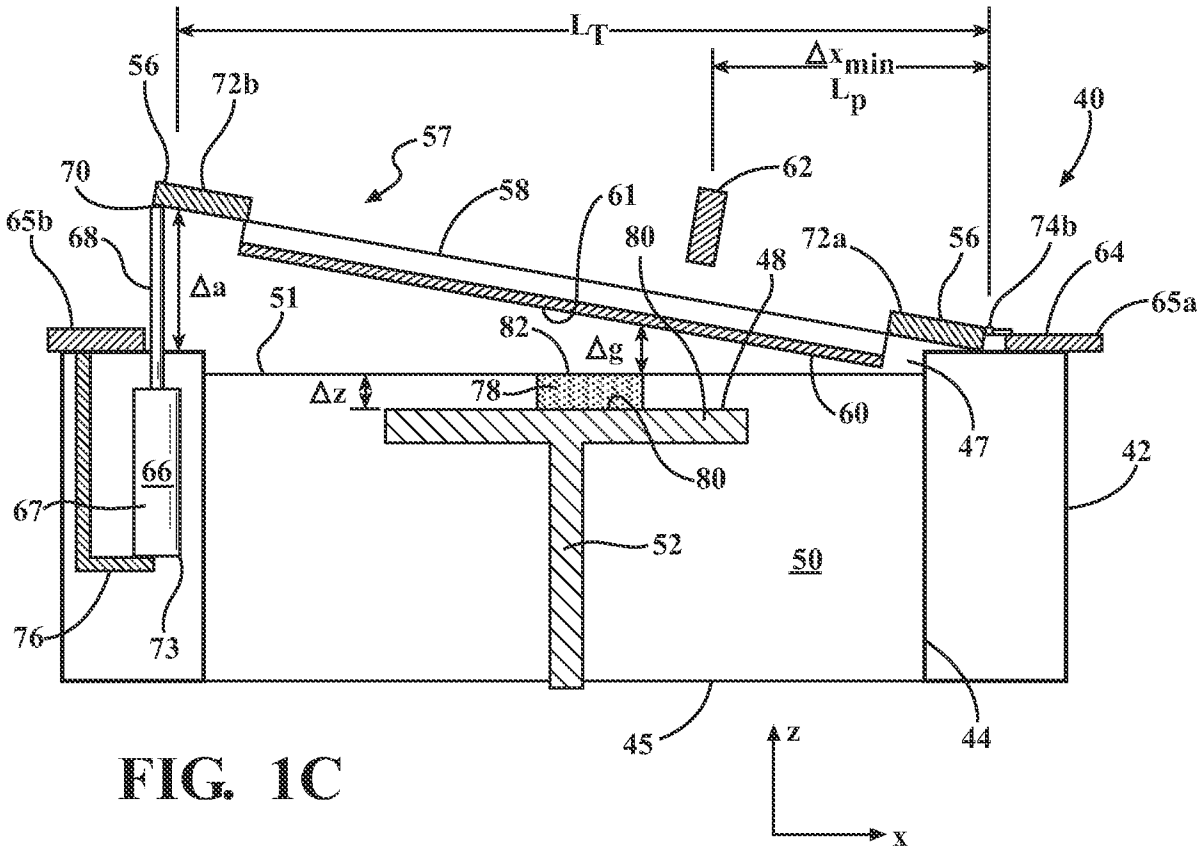

L_T
Δx_{min}
L_p
56
72b
57
70
58
61
62
40
65b
68
Δa
51
80
48
72a
56
74b
64
65a
82
Δg
Δz
78
60
47
42
66
67
52
50
76
73
80
45
44
z
x

FIG. 1C

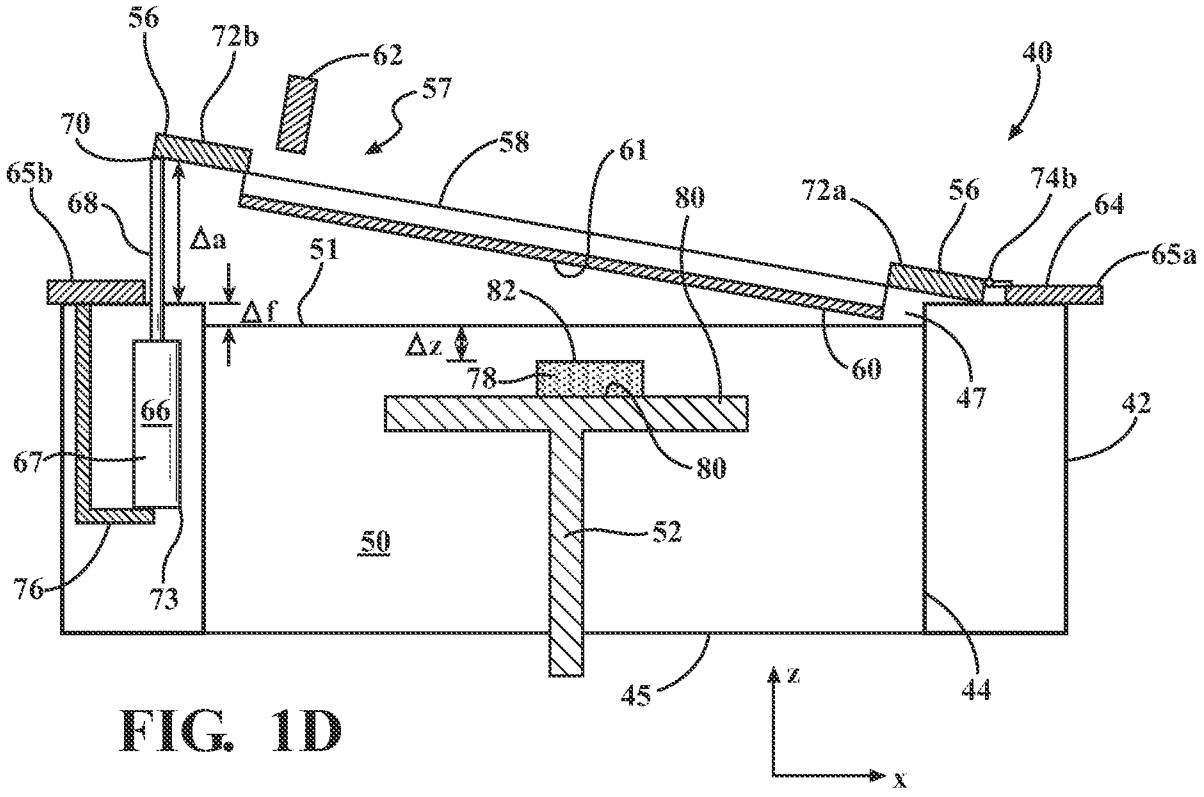

56
72b
62
57
40
70
58
61
65b
68
80
72a
56
74b
64
Δa
51
65a
82
Δf
Δz
78
60
47
42
66
67
52
50
76
73
80
45
44
z
x

FIG. 1D

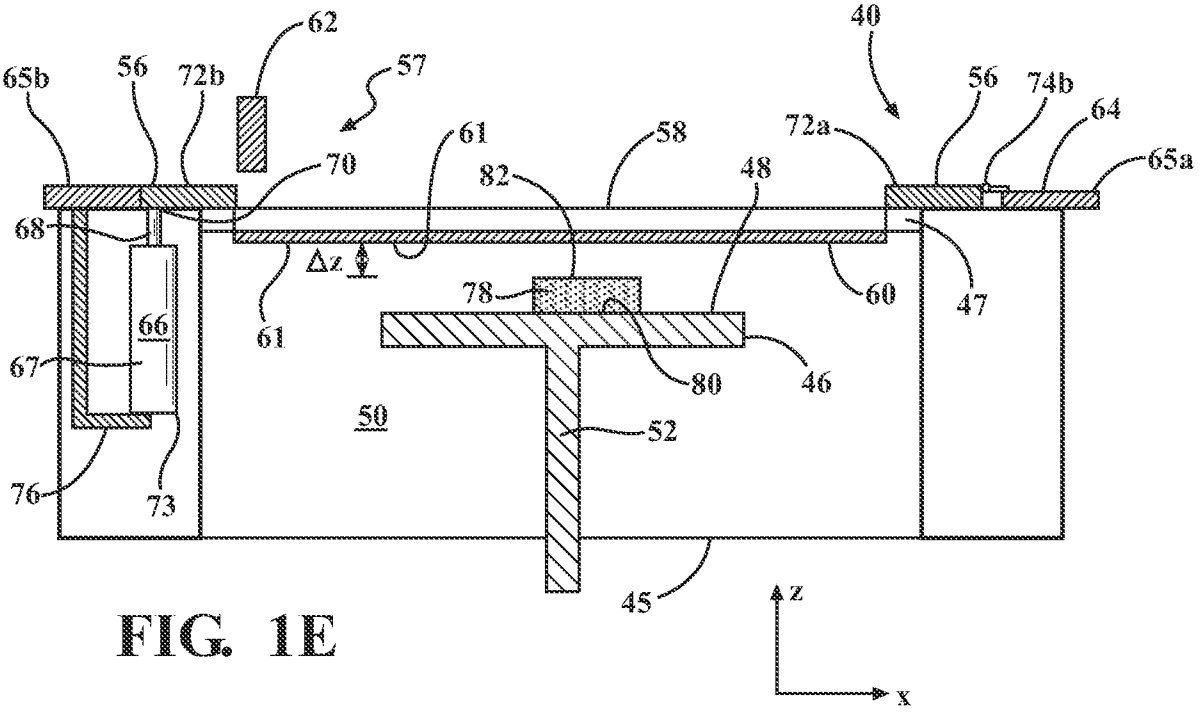

62
57
40
65b
56
72b
56
74b
64
72a
65a
70
61
58
82
48
68
Δz
78
60
47
66
61
67
80
46
50
52
76
73
45
z
x

FIG. 1E

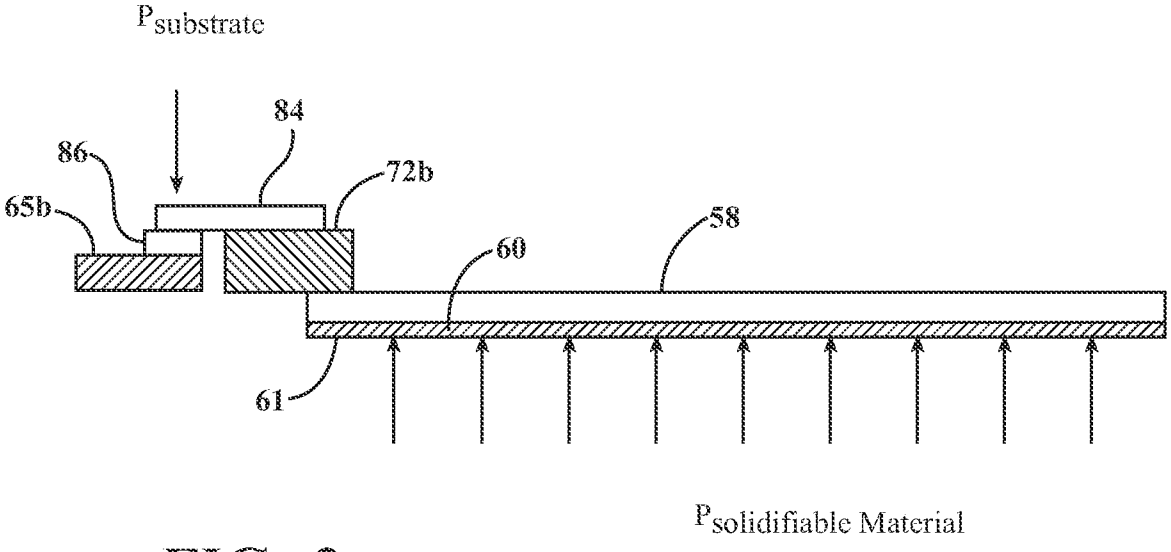

P substrate
84
86
72b
65b
58
60
61
P solidifiable Material

FIG. 2

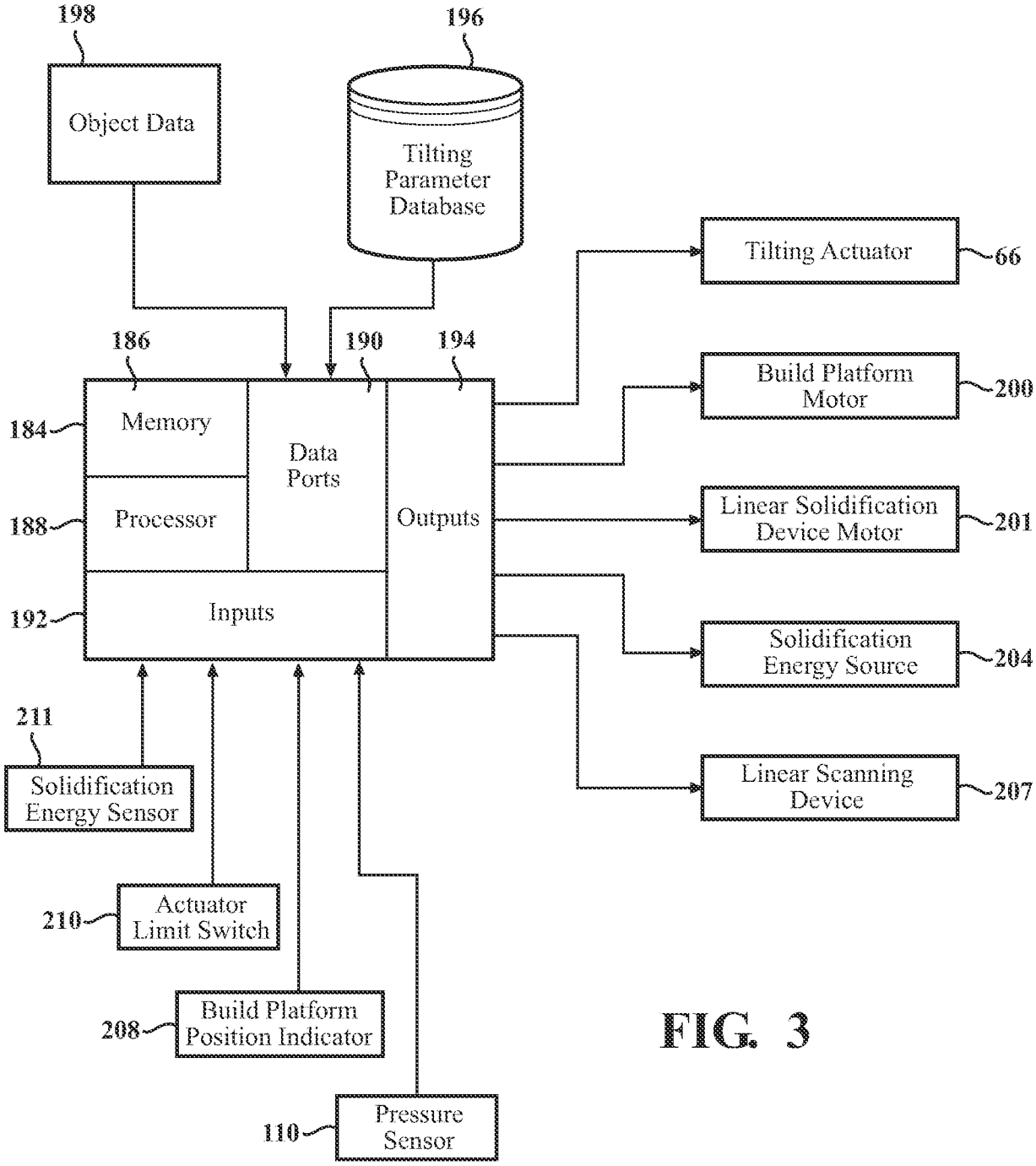

198
Object Data
196
Tilting Parameter Database
Tilting Actuator
66
186
190
194
Build Platform Motor
200
184
Memory
Data Ports
Linear Solidification Device Motor
201
188
Processor
Outputs
192
Inputs
Solidification Energy Source
204
211
Solidification Energy Sensor
Linear Scanning Device
207
210
Actuator Limit Switch
208
Build Platform Position Indicator
110
Pressure Sensor

FIG. 3

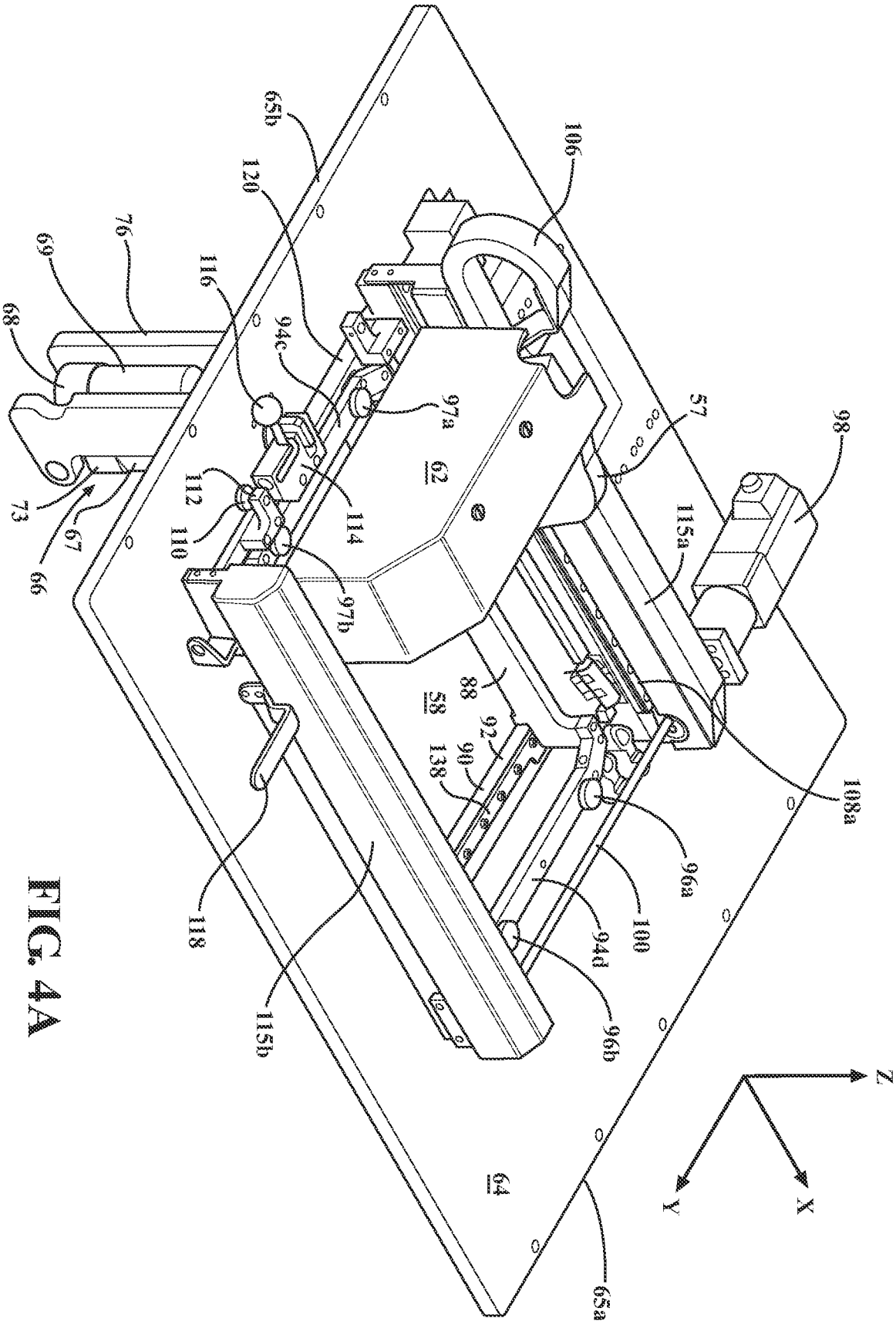

65b
120
106
76
69
116
68
94c
97a
62
57
98
73
97
66
112
110
114
97b
115a
88
58
92
90
138
108a
96a
118
100
94d
115b
96b
64
65a
Z
Y
X

FIG. 4A

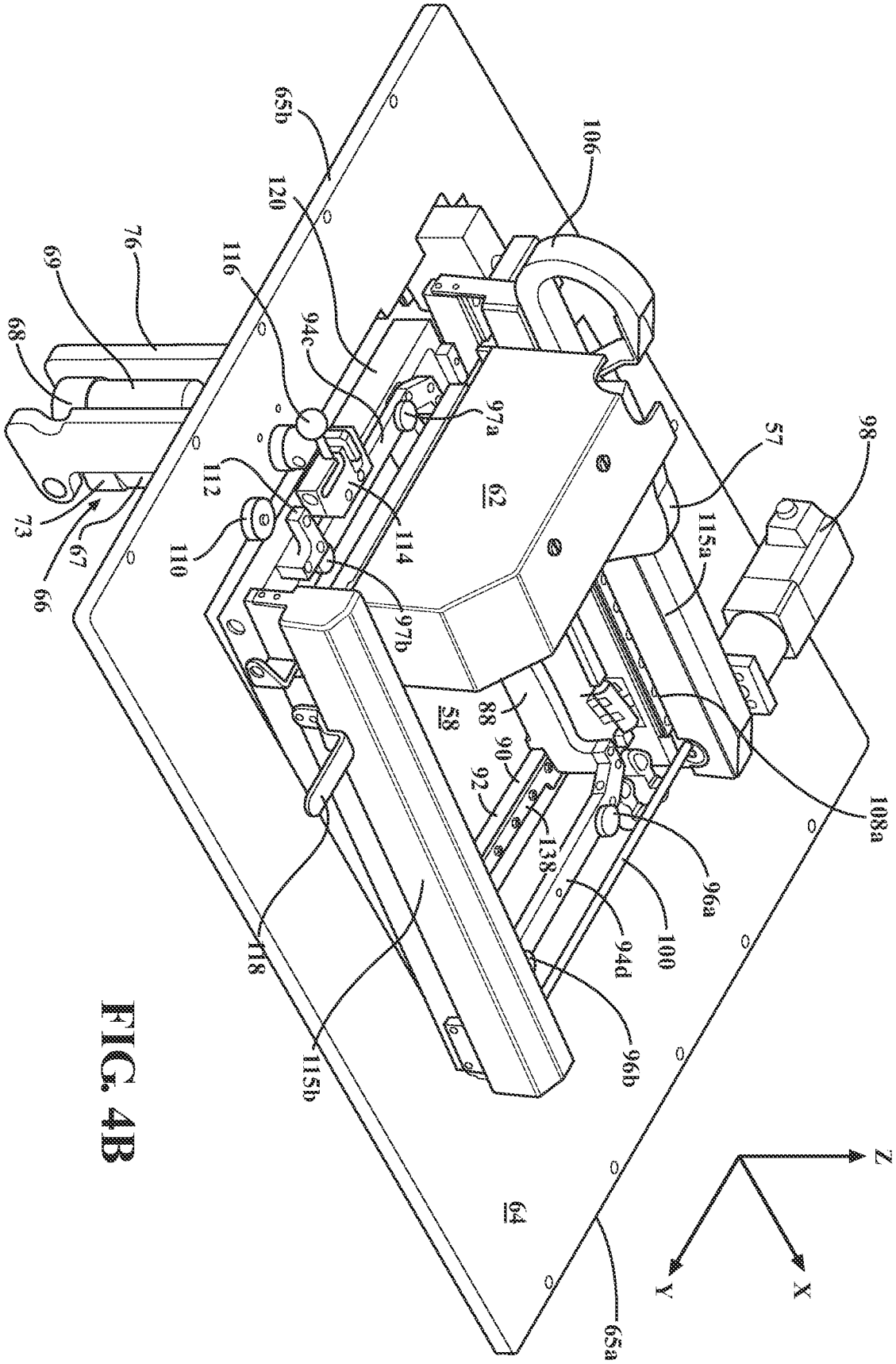

65b
120
106
76
69
116
94c
68
97a
112
62
57
98
73
67
66
110
114
115a
97b
58
88
90
92
138
108a
96a
118
94d
100
115b
96b
64
65a
Z
Y
X

FIG. 4B

FIG. 4C

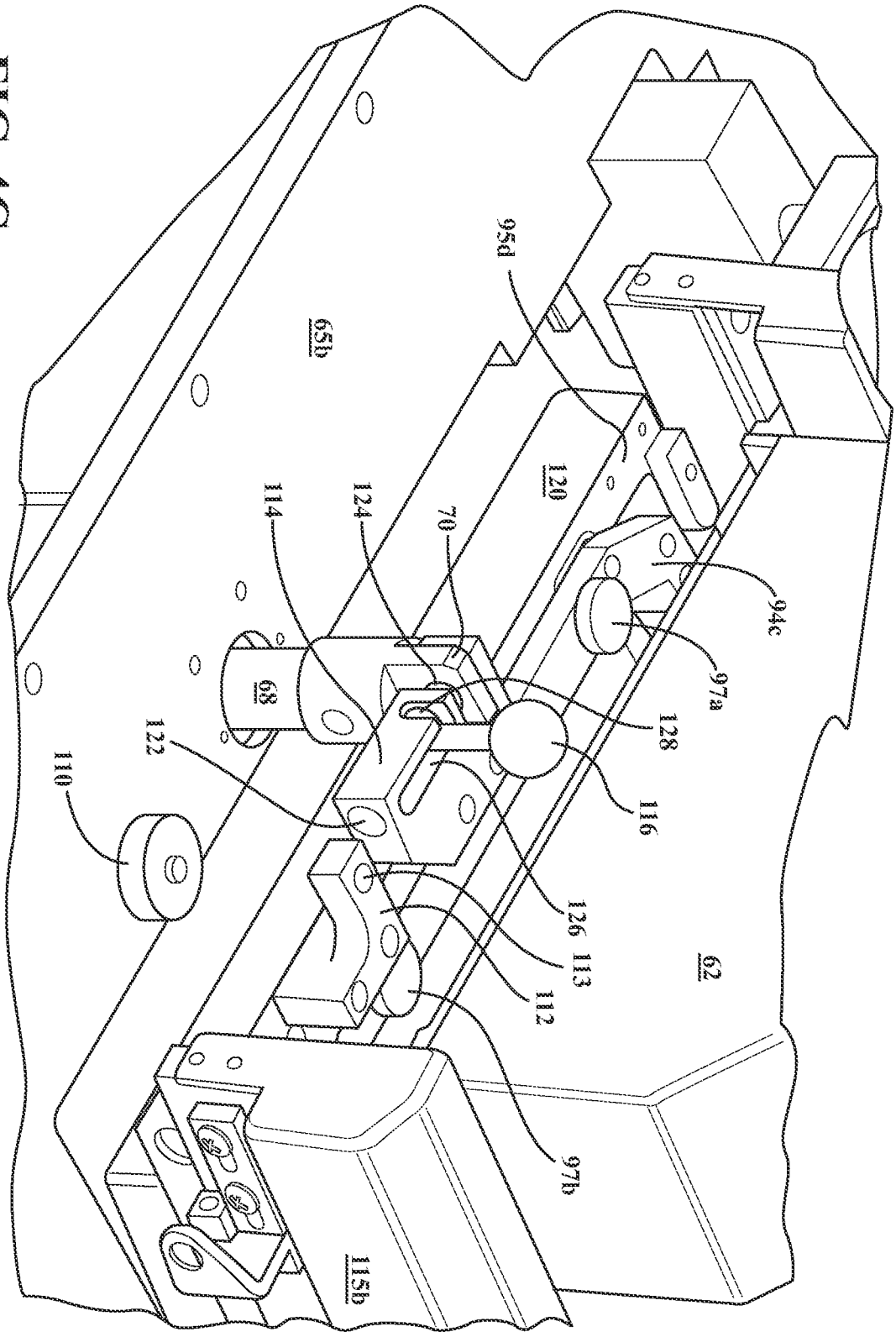

95d
65b
120
114
124
70
94c
97a
68
128
122
110
116
126
113
112
62
97b
115b

FIG. 4D

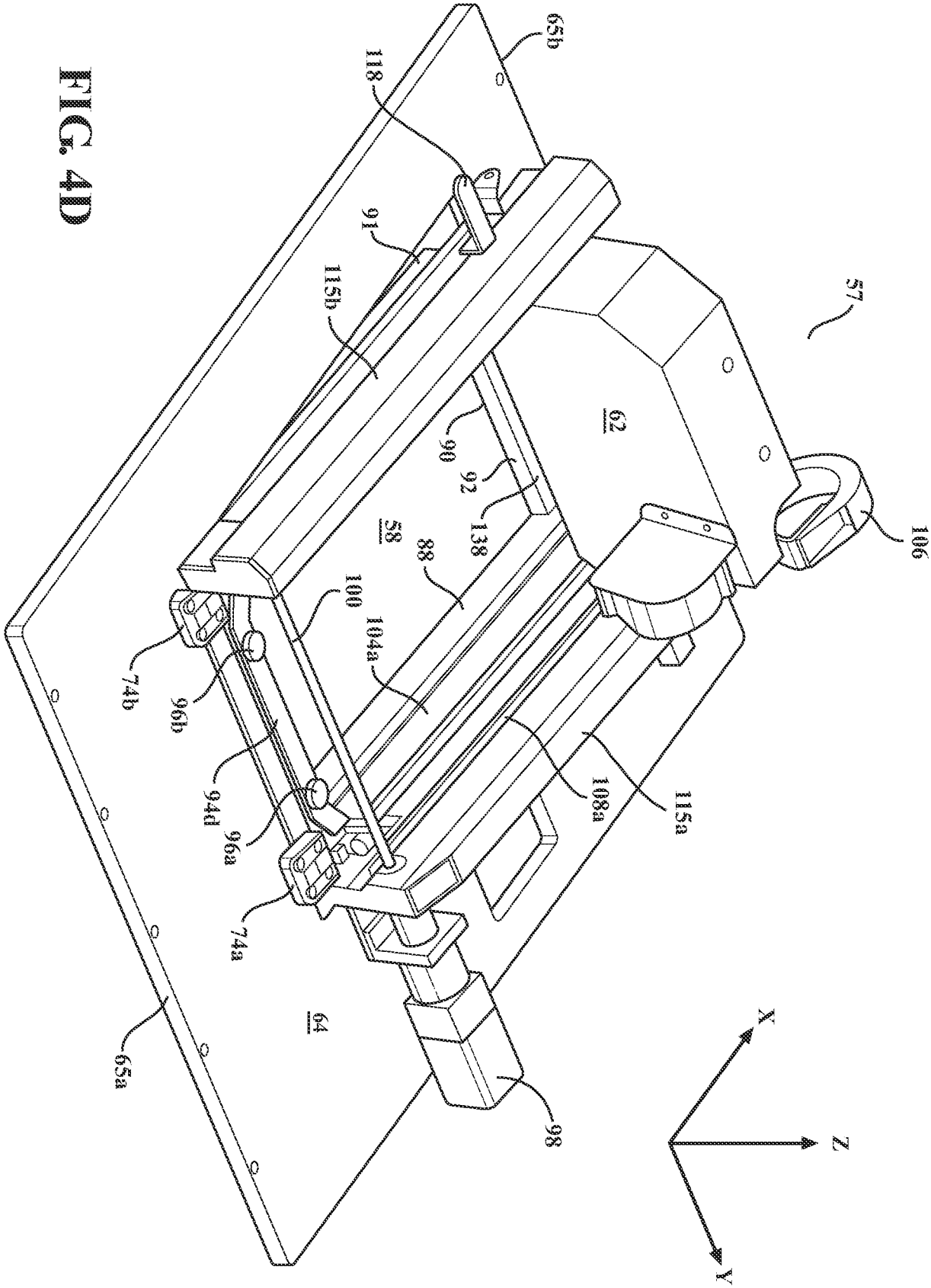

65b
118
91
115b
57
62
90
92
138
106
58
88
100
104a
74b
96b
94d
96a
74a
108a
115a
64
65a
98
Y
Z
Y

FIG. 4E

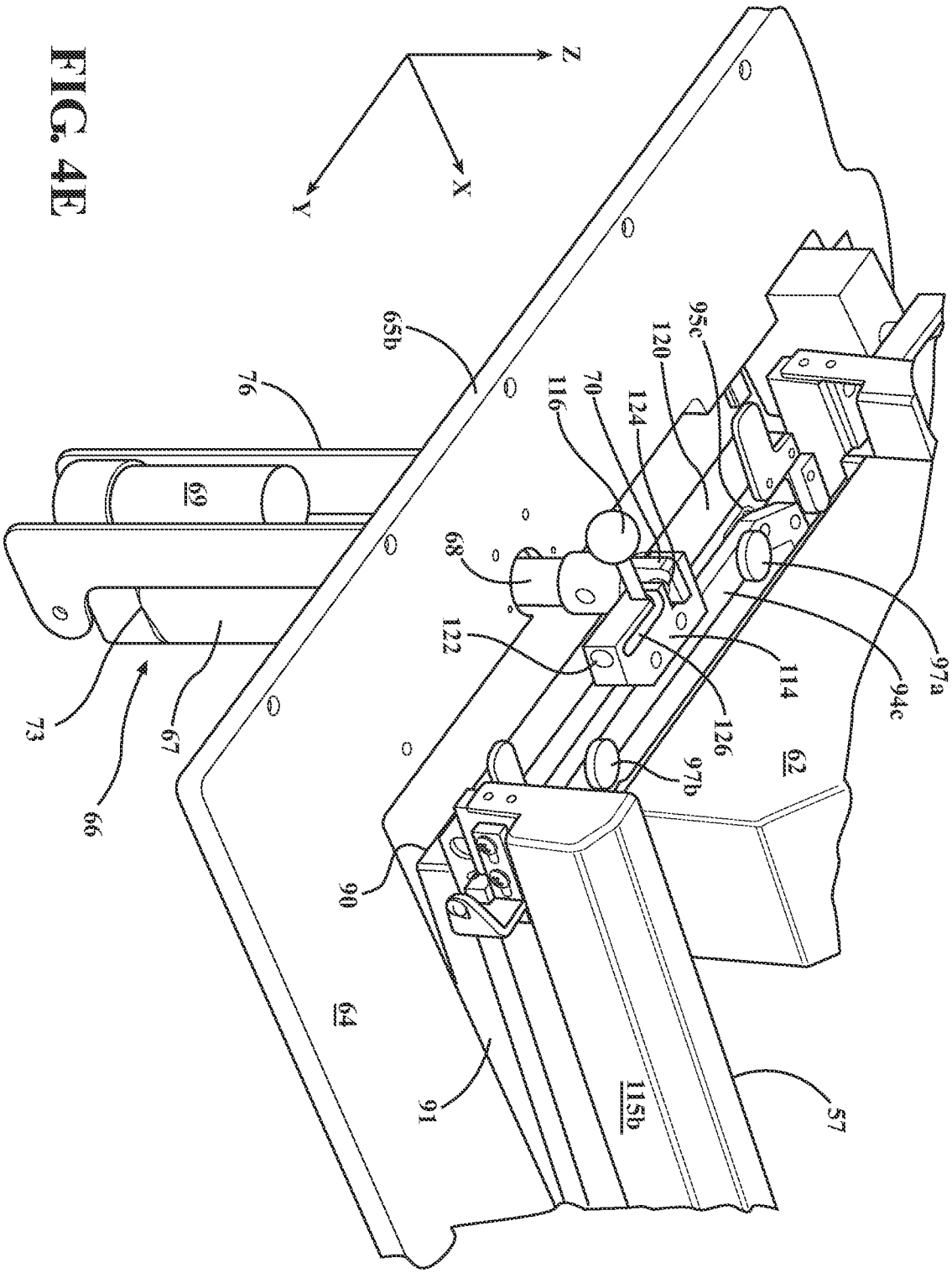
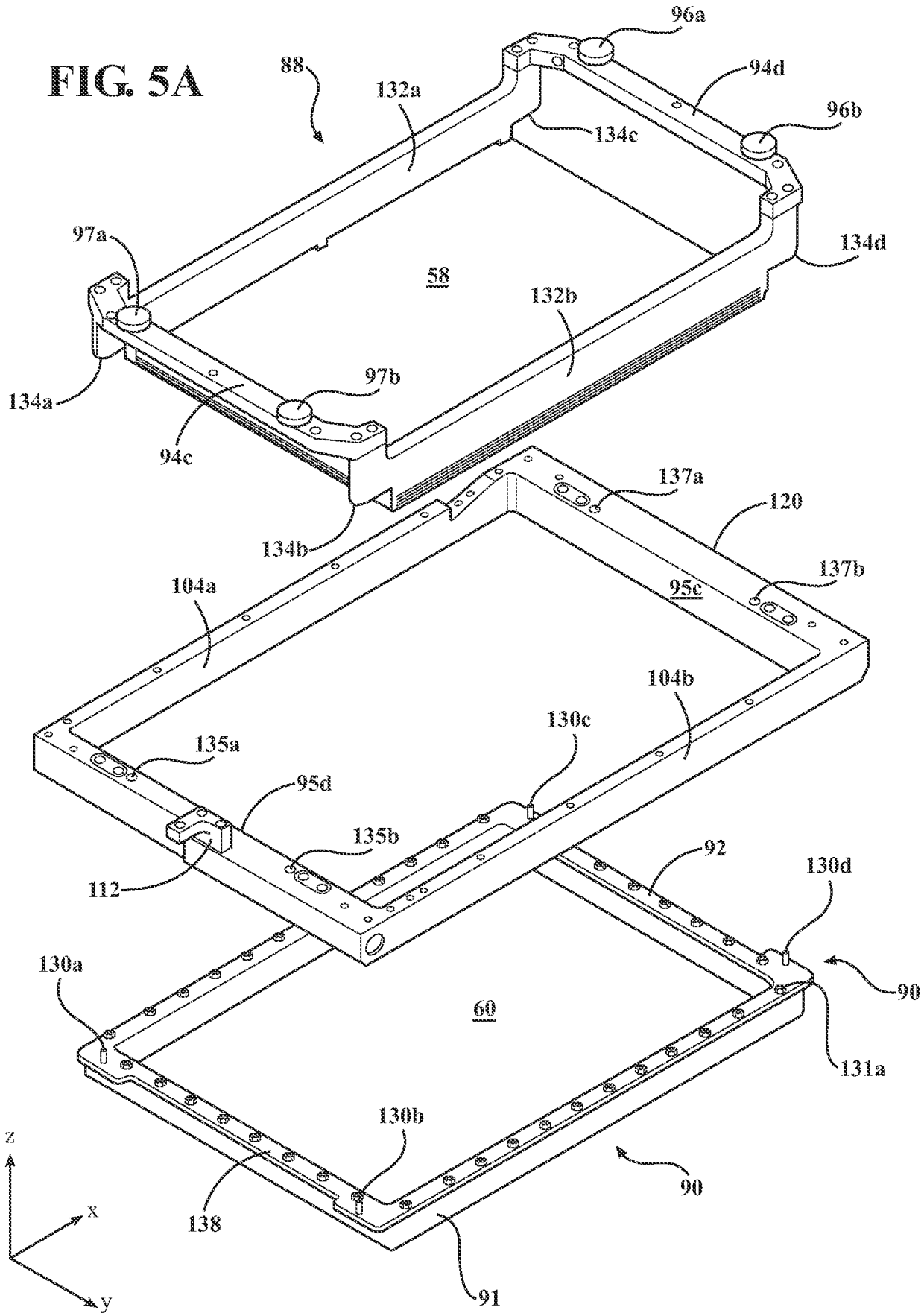

Z
X
Y
65b
76
69
73
97
66
68
122
116
70
124
120
95c
114
126
97b
94c
97a
62
90
64
91
115b
57

FIG. 5A


96a
88
94d
132a
96b
134c
97a
134d
58
132b
97b
134a
94c
137a
120
134b
137b
104a
95c
104b
130c
135a
95d
135b
92
130d
112
130a
90
60
131a
130b
z
x
138
90
y
91

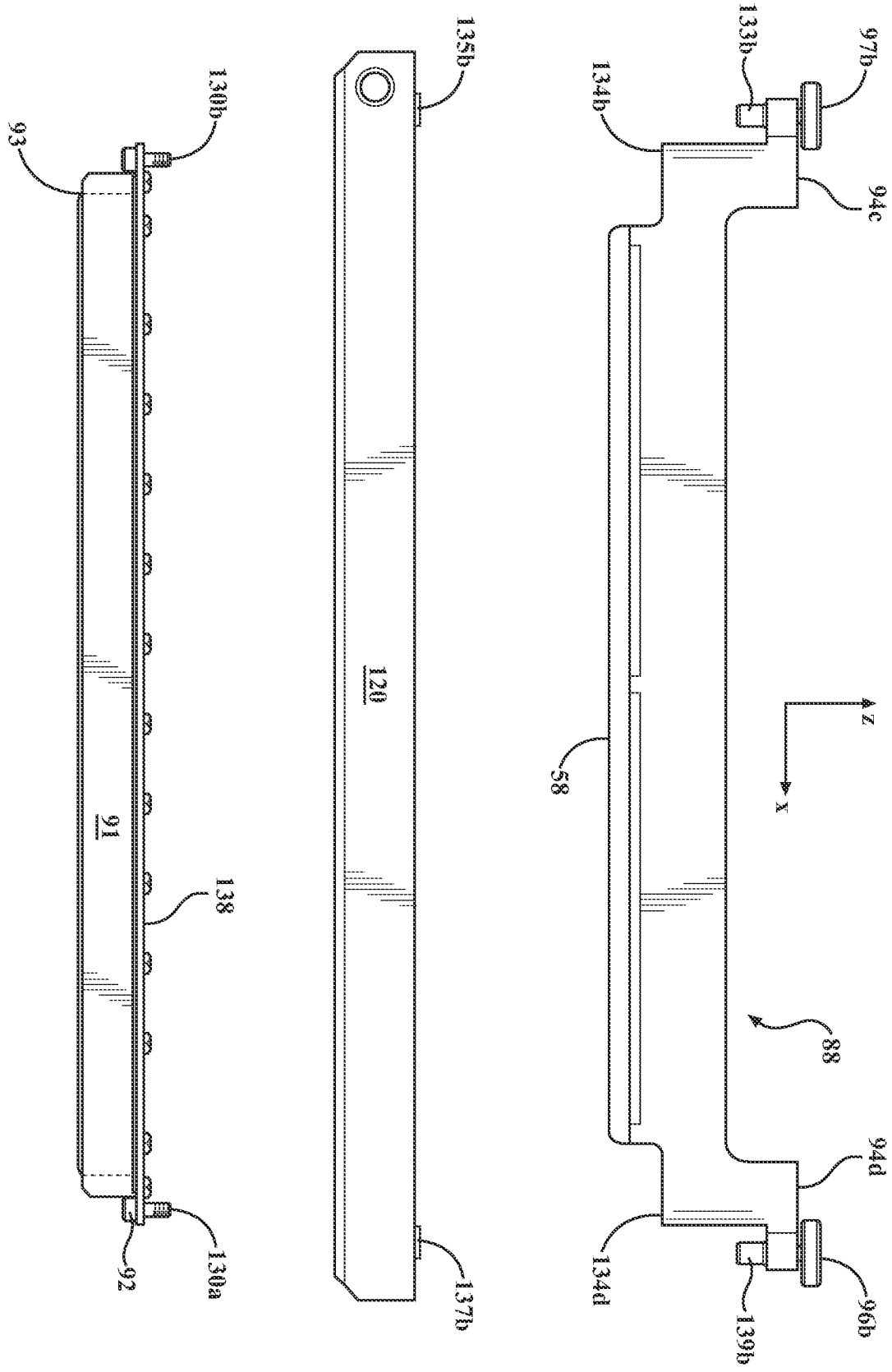

133b
97b
134b
94c
z
x
58
88
94d
134d
139b
96b
135b
120
137b
130b
93
91
138
92
130a

FIG. 5B

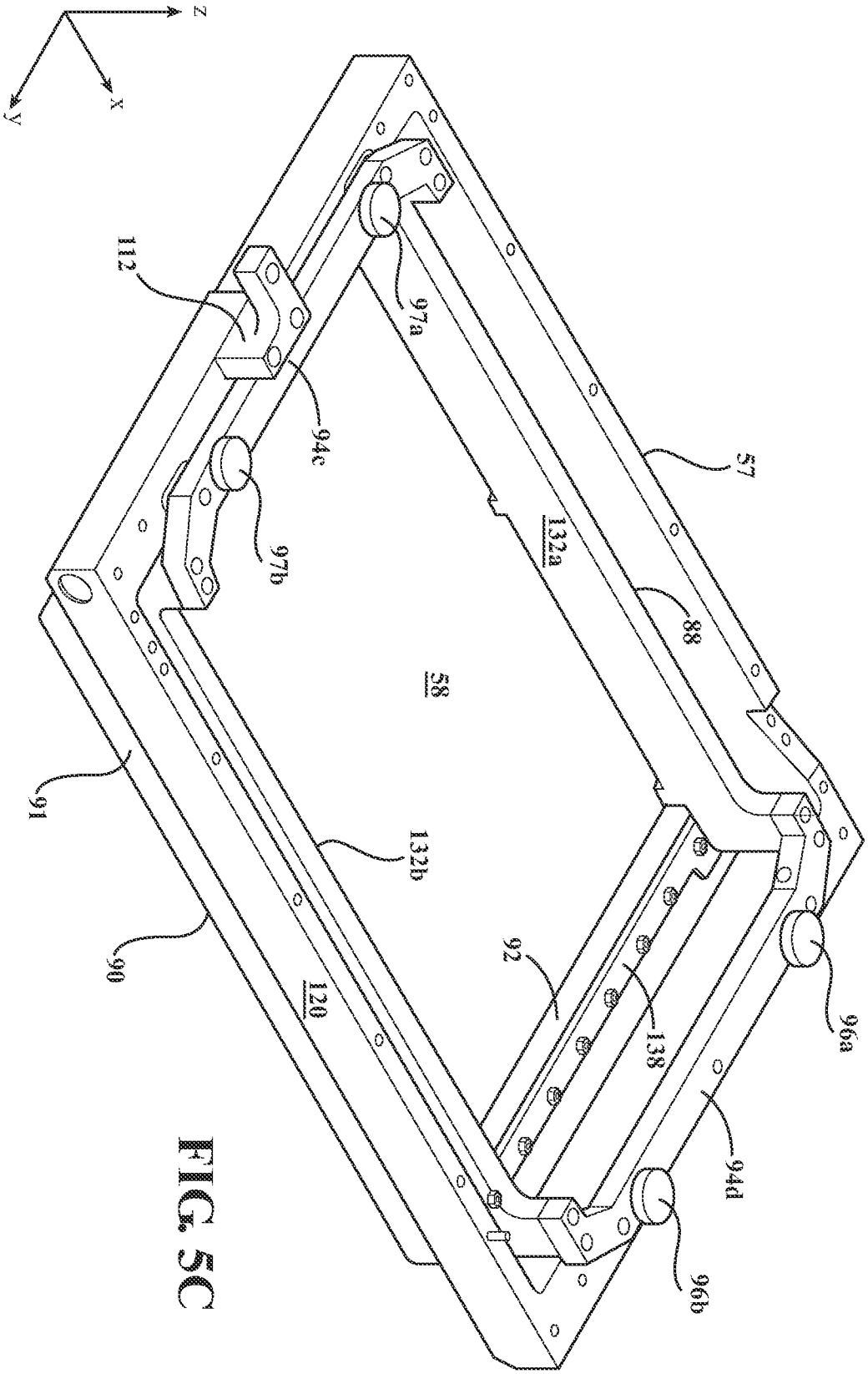

Z
X
Y
112
97a
94c
97b
57
132a
88
58
91
132b
90
120
92
138
96a
94d
96b

FIG. 5C

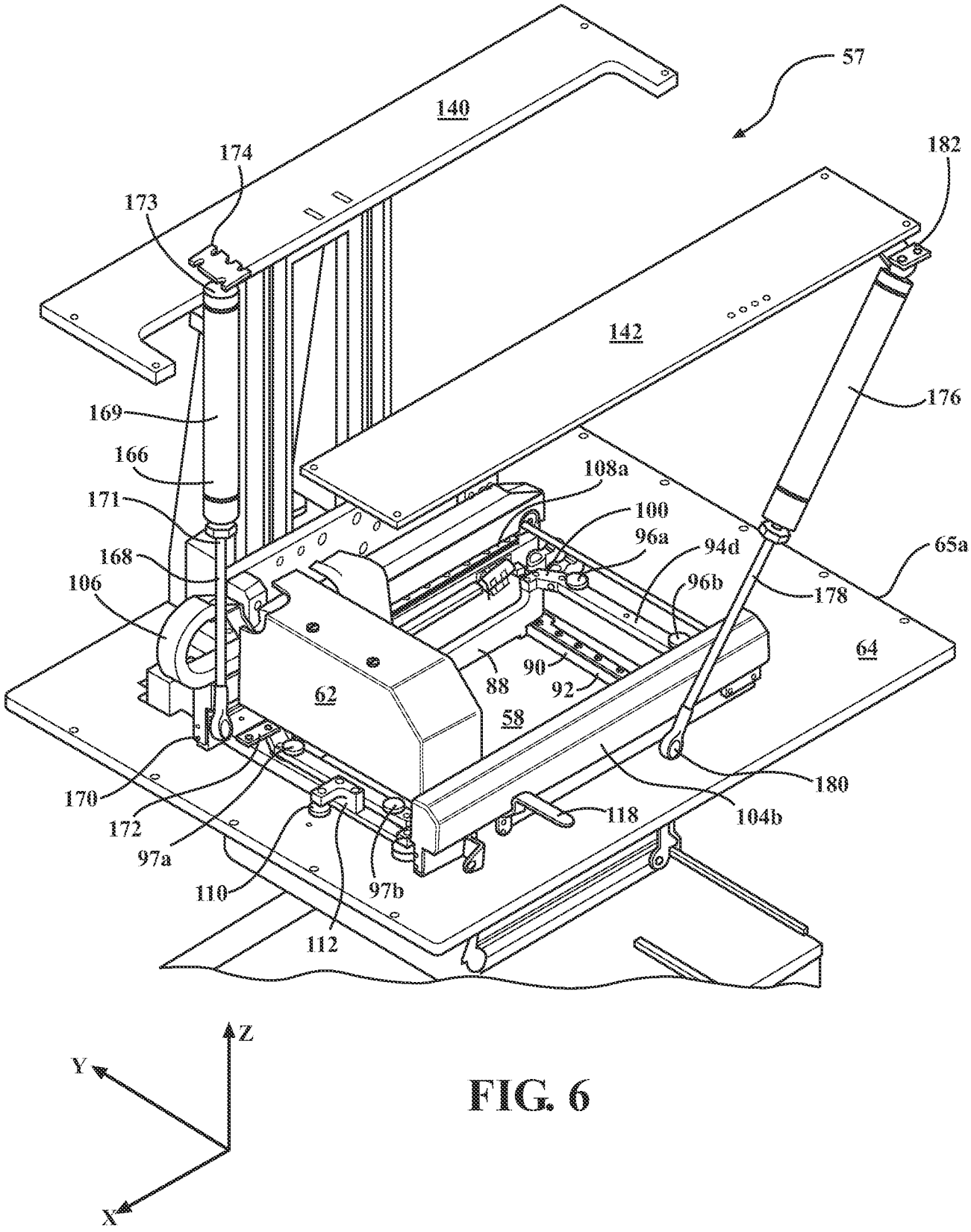

57
140
174
173
182
142
176
169
166
171
168
106
108a
100
96a
94d
96b
178
65a
64
62
88
90
92
58
180
104b
118
170
172
97a
110
97b
112
Z
Y
X

FIG. 6

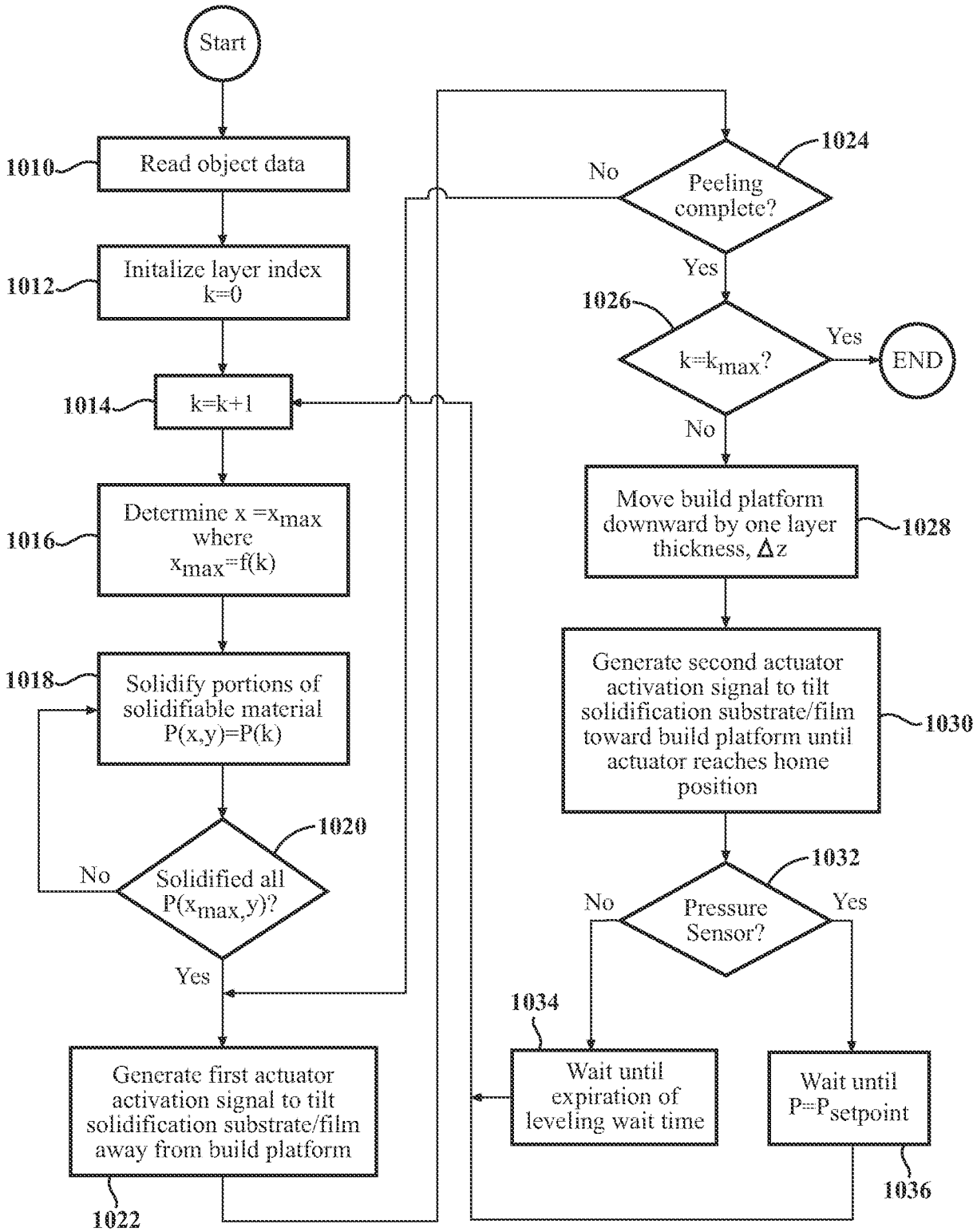

Start
1010
Read object data
1012
Initalize layer index
k=0
1014
k=k+1
1016
Determine x =xmax
where
xmax=f(k)
1018
Solidify portions of
solidifiable material
P(x,y)=P(k)
1020
No
Solidified all
P(xmax,y)?
Yes
Generate first actuator
activation signal to tilt
solidification substrate/film
away from build platform
1022
1024
No
Peeling
complete?
Yes
1026
k=kmax?
Yes
END
No
Move build platform
downward by one layer
thickness, Δz
1028
Generate second actuator
activation signal to tilt
solidification substrate/film
toward build platform until
actuator reaches home
position
1030
1032
No
Pressure
Sensor?
Yes
1034
Wait until
expiration of
leveling wait time
Wait until
P=Psetpoint
1036

FIG. 7

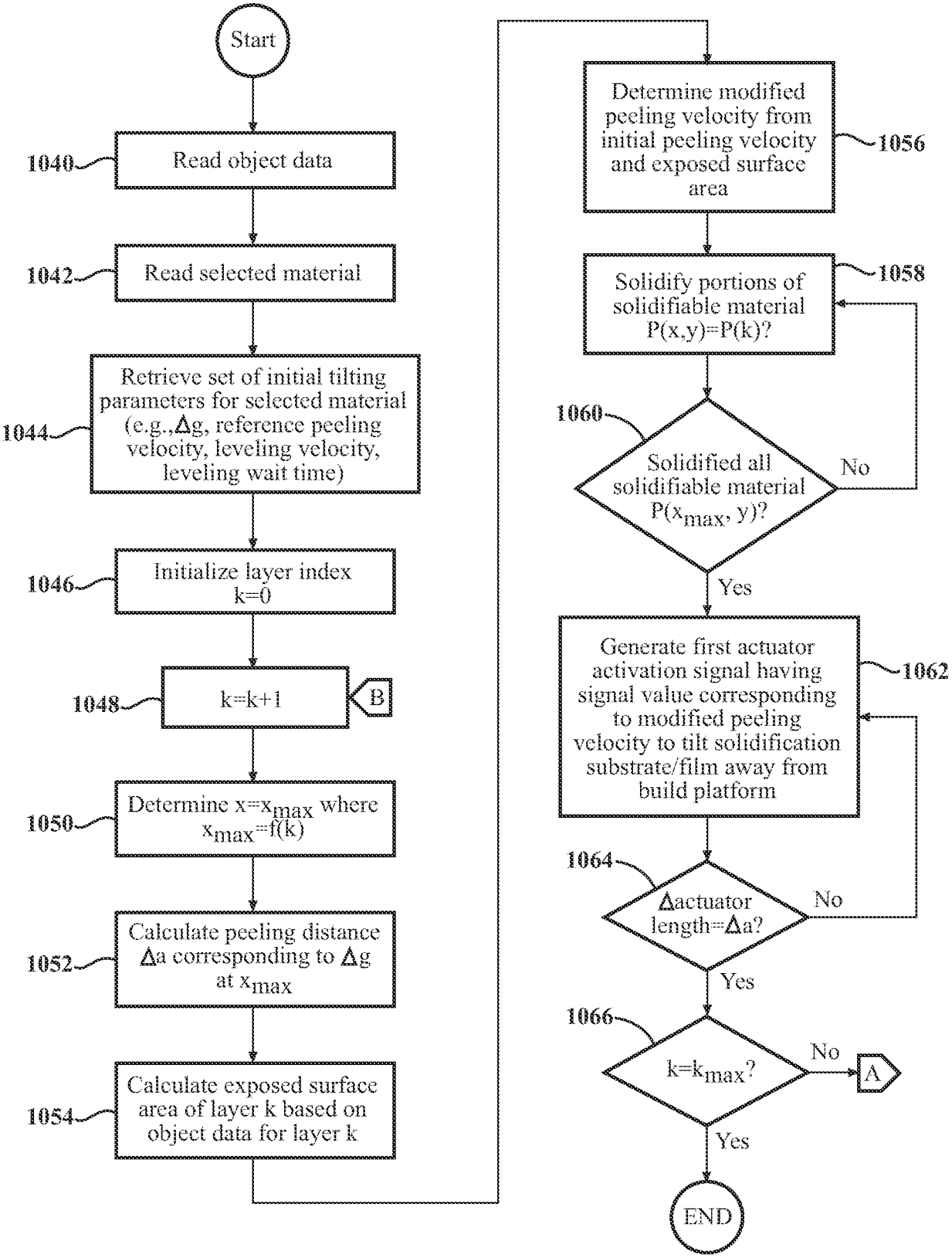

Start
1040
Read object data
1042
Read selected material
1044
Retrieve set of initial tilting parameters for selected material (e.g.,Δg, reference peeling velocity, leveling velocity, leveling wait time)
1046
Initialize layer index k=0
1048
k=k+1
B
1050
Determine x=x_{max} where x_{max}=f(k)
1052
Calculate peeling distance Δa corresponding to Δg at x_{max}
1054
Calculate exposed surface area of layer k based on object data for layer k
1056
Determine modified peeling velocity from initial peeling velocity and exposed surface area
1058
Solidify portions of solidifiable material P(x,y)=P(k)?
1060
Solidified all solidifiable material P(x_{max}, y)?
No
Yes
1062
Generate first actuator activation signal having signal value corresponding to modified peeling velocity to tilt solidification substrate/film away from build platform
1064
Δactuator length=Δa?
No
Yes
1066
k=k_{max}?
No
A
Yes
END

FIG. 8A

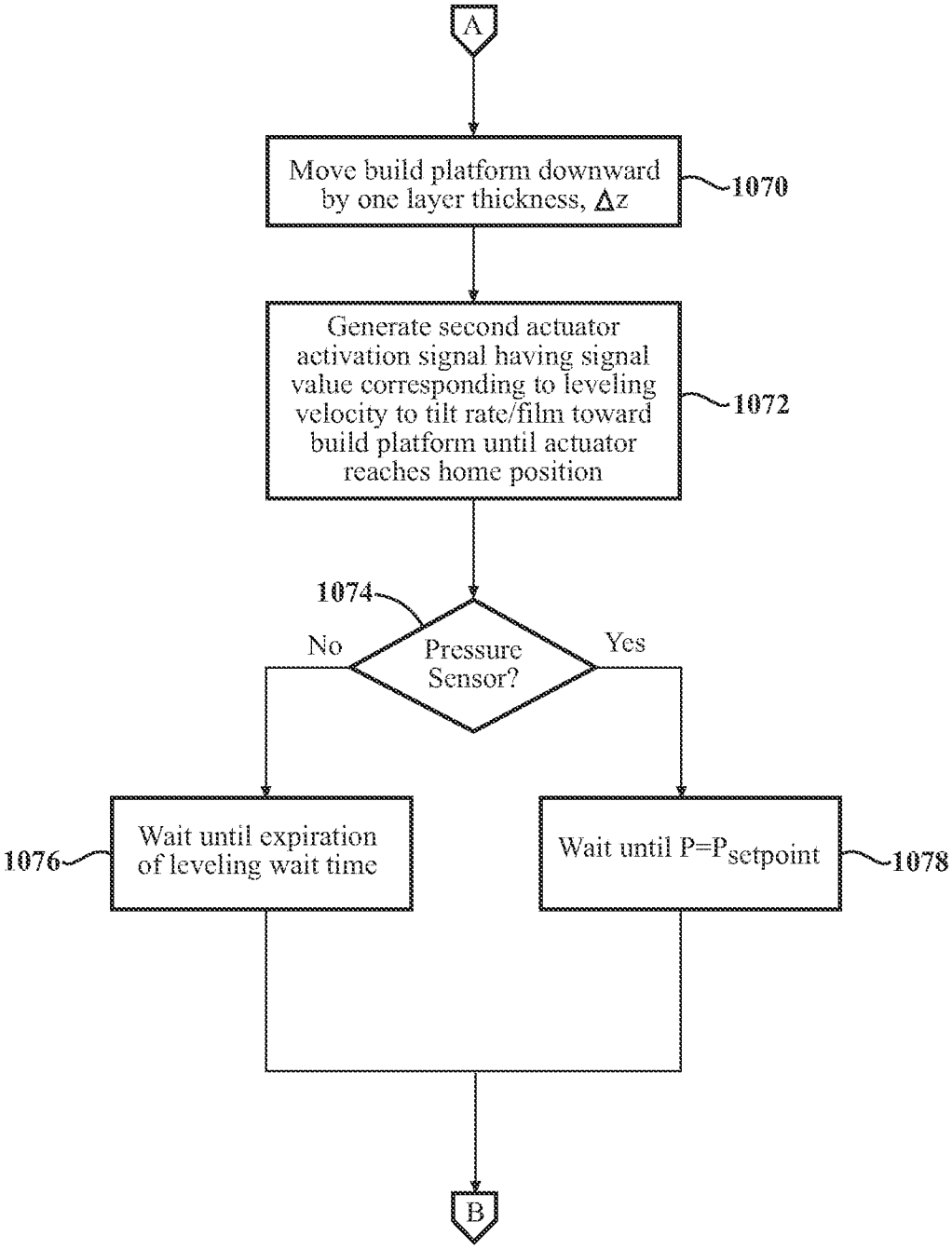

A
Move build platform downward by one layer thickness, Δz
1070
Generate second actuator activation signal having signal value corresponding to leveling velocity to tilt rate/film toward build platform until actuator reaches home position
1072
1074
Pressure Sensor?
No
Yes
Wait until expiration of leveling wait time
1076
Wait until P=Psetpoint
1078
B

FIG. 8B


196
215a
215b
215c
216a
216b
216c
216d
216e
216f
Material
Minimum object peeling travel distance (mm)
Peeling velocity (mm/sec)
Leveling velocity (mm/sec)
Leveling wait time (seconds)
Reference squeezing pressure (psi)
Envisiontec E-Denstone
2.4
12.7
12.7
10
80
Envisiontec Clear Guide
3.0
10.2
10.2
8
80
Envisiontec E-Dent
3.5
8
6
11
75

FIG. 9

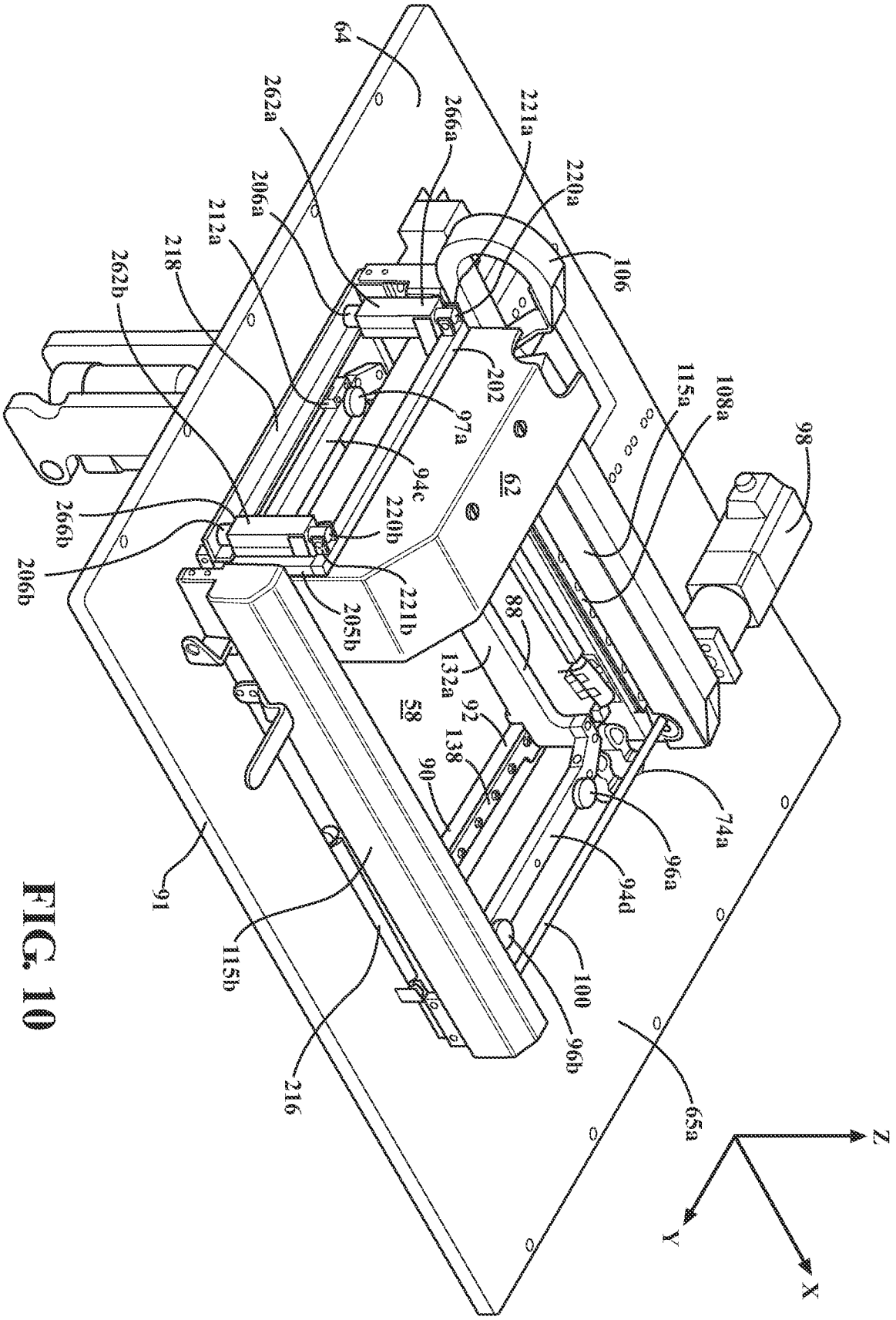

64
262a
266a
221a
220a
206a
212a
218
262b
106
202
97a
94c
62
266b
220b
206b
221b
205b
115a
108a
98
88
132a
92
58
138
90
74a
96a
94d
91
115b
100
96b
216
65a
Z
Y
X

FIG. 10

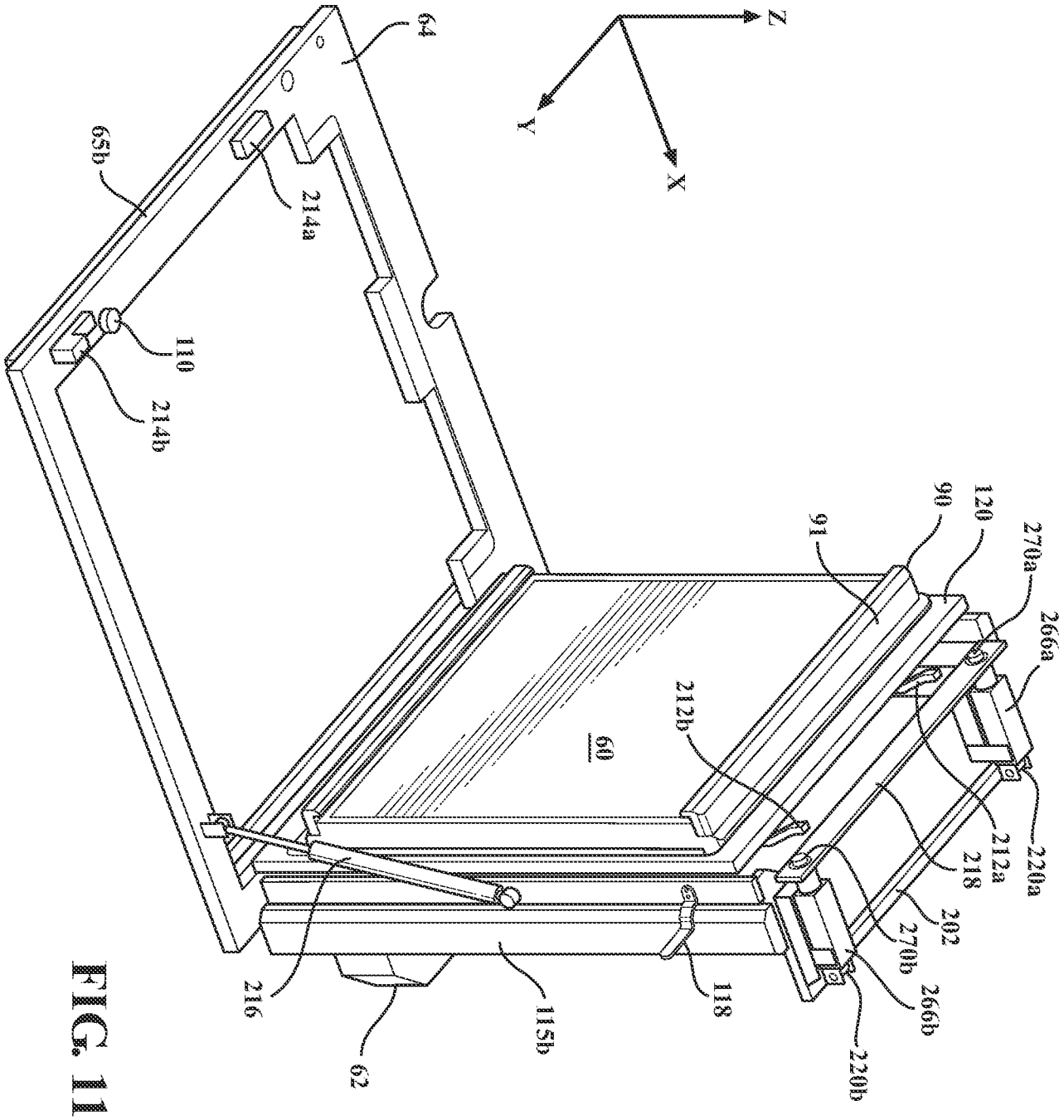

Z
Y
X
64
65b
214a
110
214b
90
120
91
270a
266a
212b
60
212a
218
220a
202
270b
266b
220b
118
115b
216
62

FIG. 11

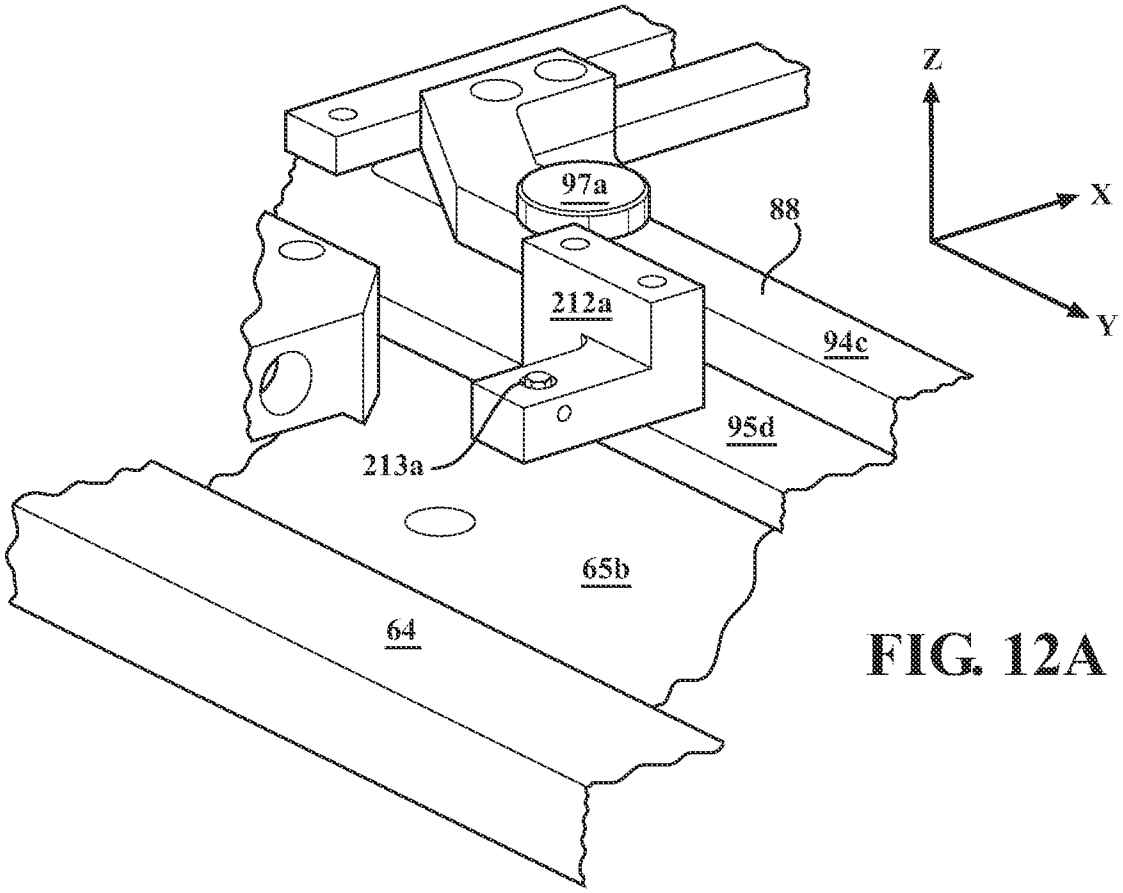


FIG. 12A

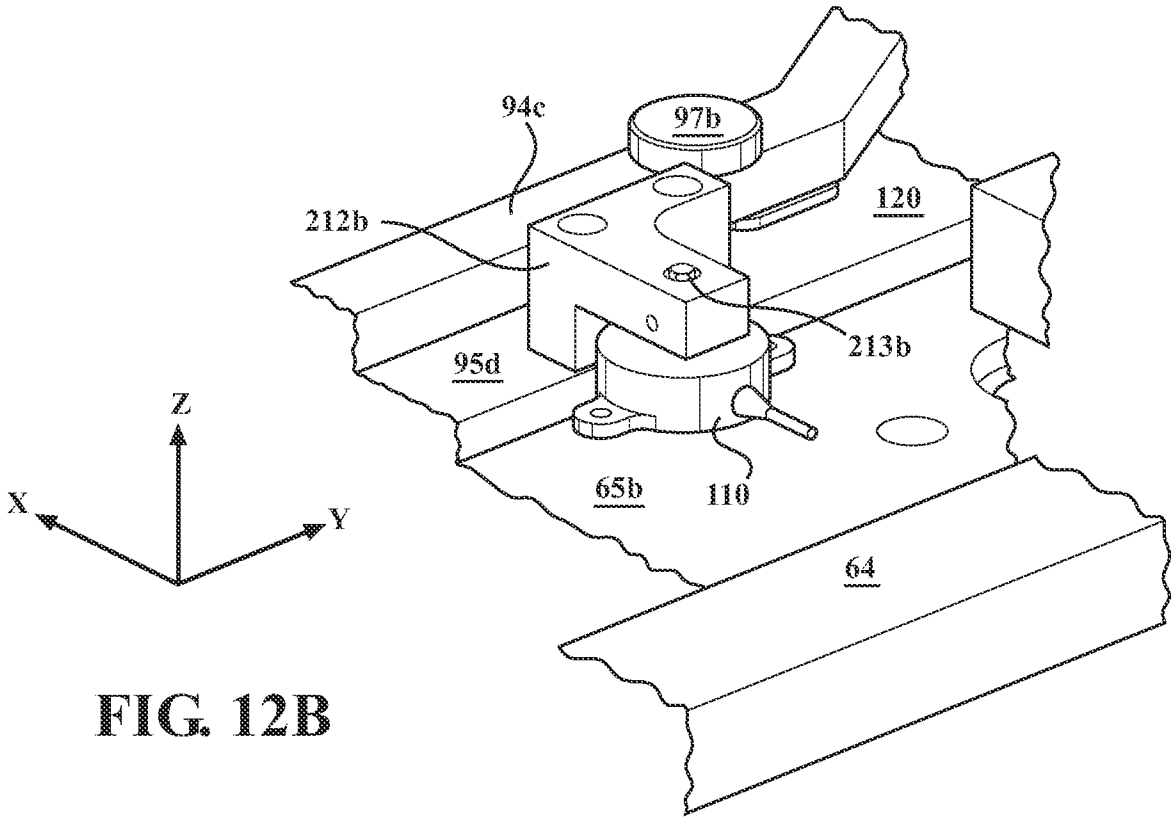


FIG. 12B

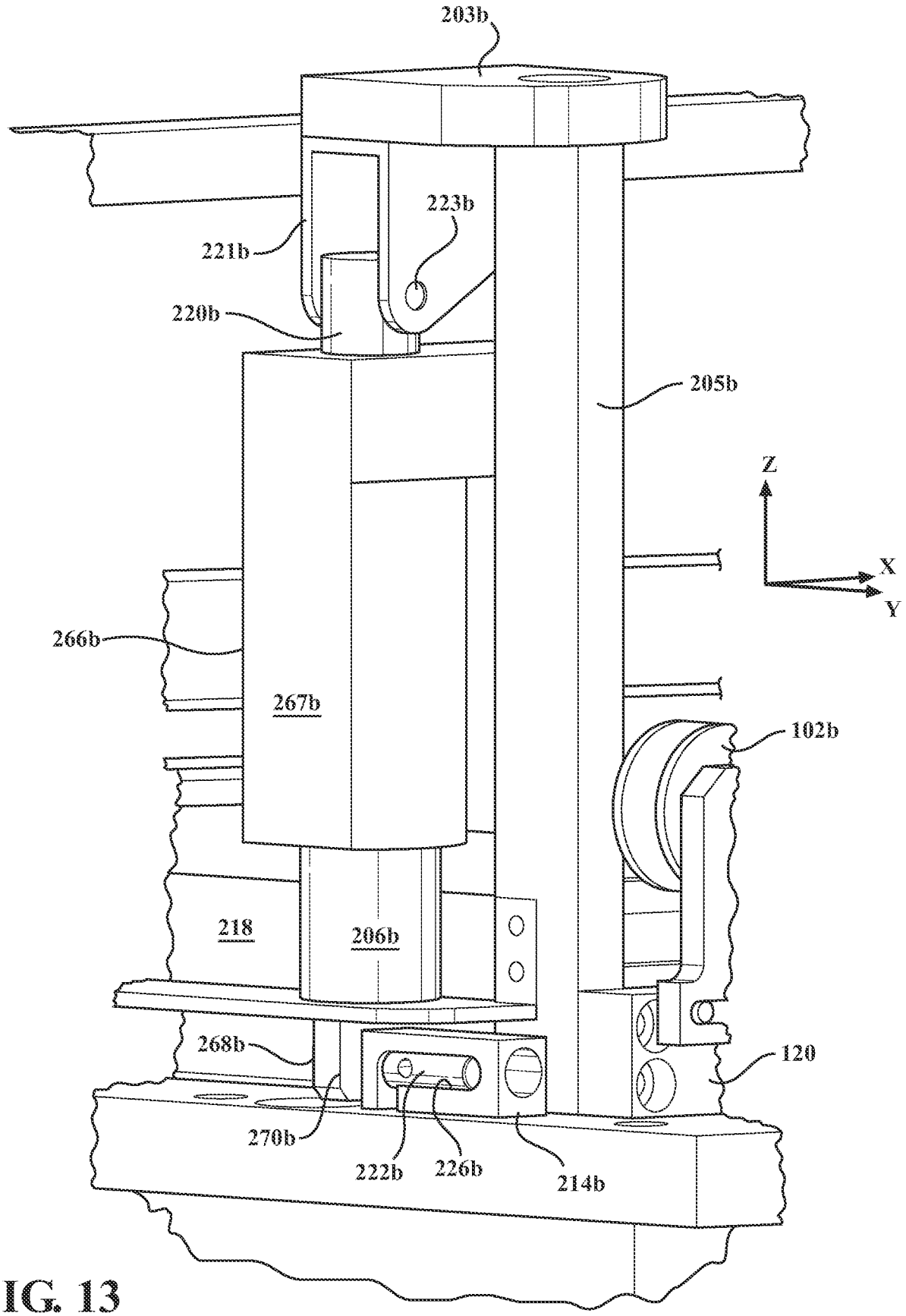

203b
223b
221b
220b
205b
Z
X
Y
266b
267b
102b
218
206b
268b
120
270b
222b
226b
214b

FIG. 13

FIG. 14A

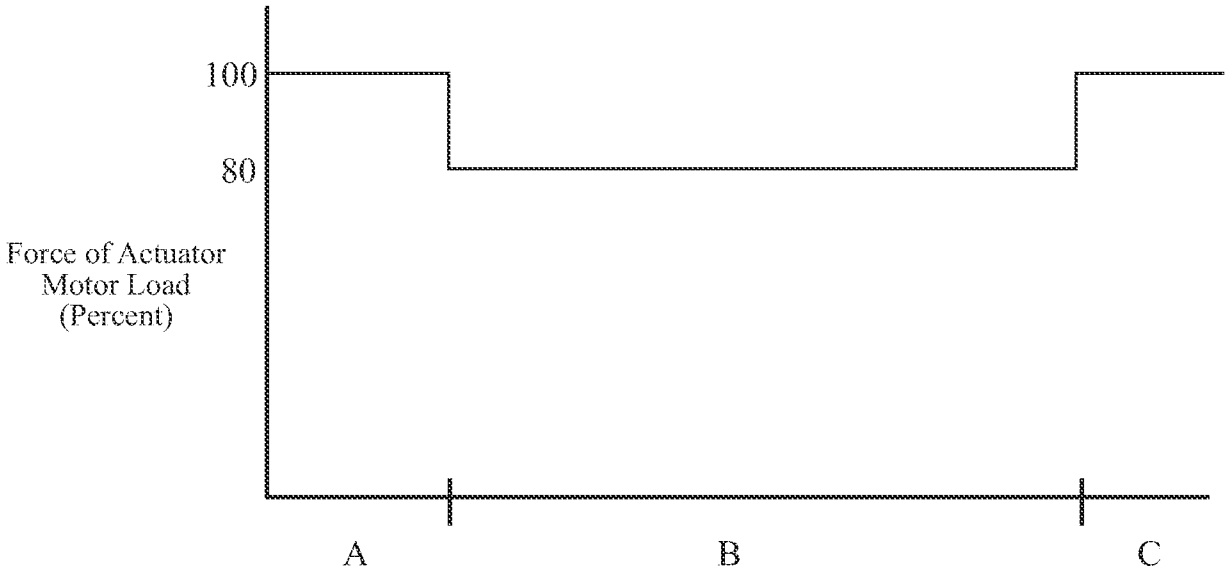


FIG. 14B

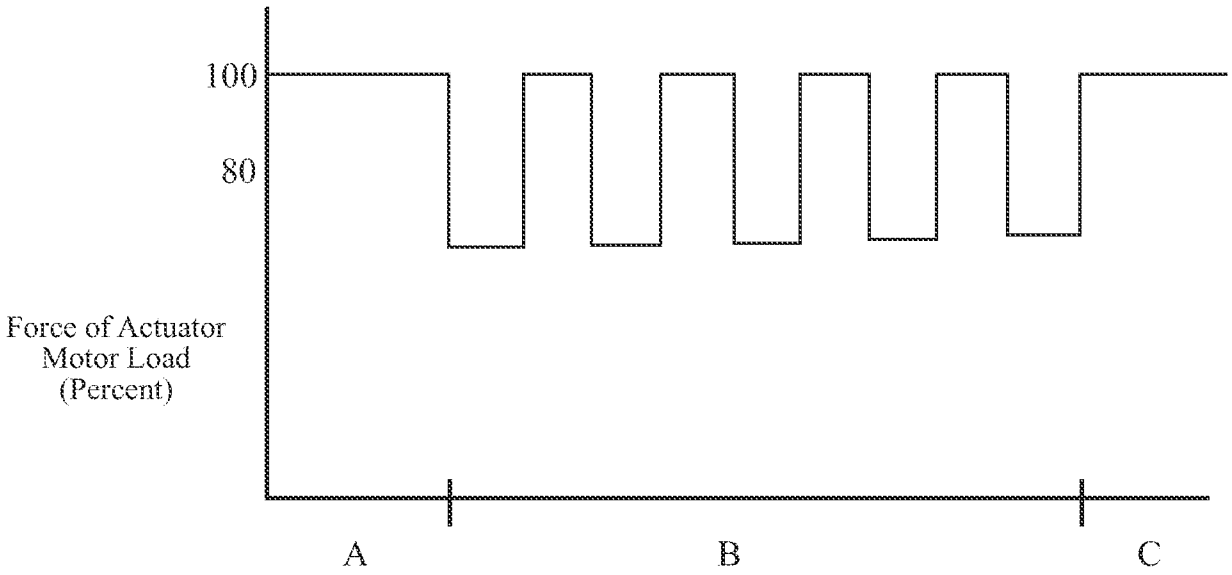
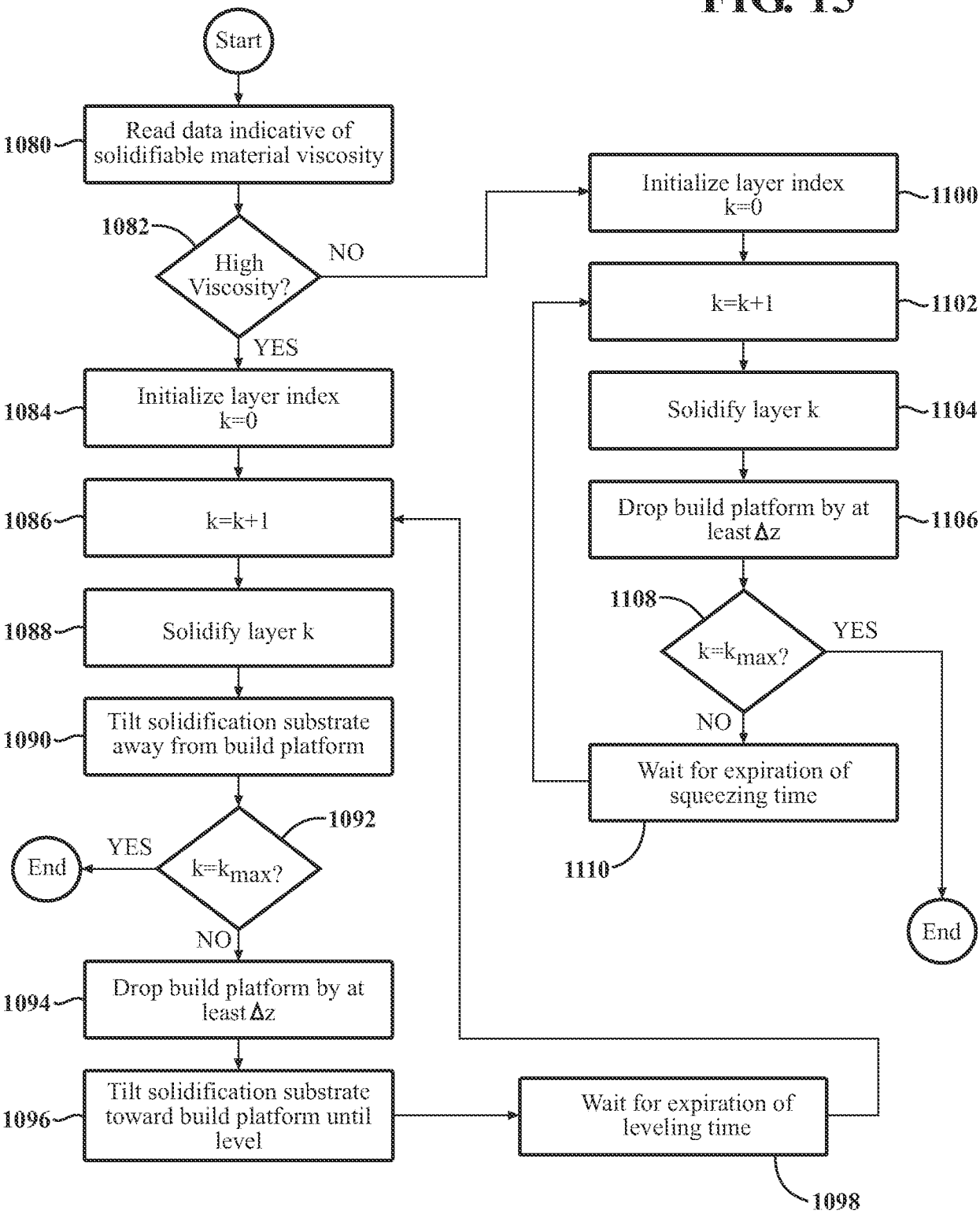


FIG. 15


Start
1080
Read data indicative of solidifiable material viscosity
1082
High Viscosity?
NO
YES
1084
Initialize layer index k=0
1086
k=k+1
1088
Solidify layer k
1090
Tilt solidification substrate away from build platform
1092
k=kmax?
YES
End
NO
1094
Drop build platform by at least Δz
1096
Tilt solidification substrate toward build platform until level
Wait for expiration of leveling time
1098
Initialize layer index k=0
1100
k=k+1
1102
Solidify layer k
1104
Drop build platform by at least Δz
1106
1108
k=kmax?
YES
NO
Wait for expiration of squeezing time
1110
End

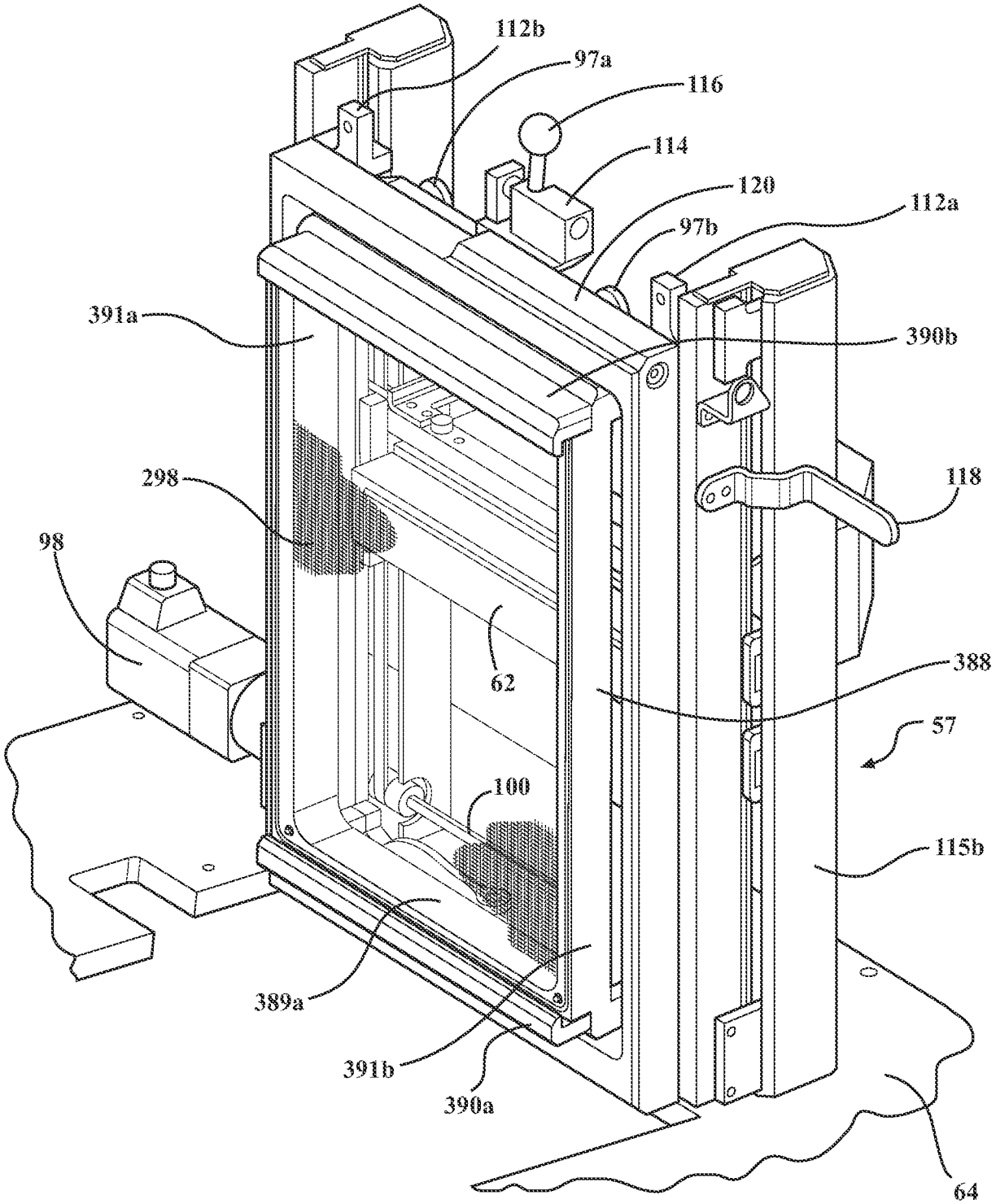

112b
97a
116
114
120
112a
97b
391a
390b
298
118
98
62
388
57
100
115b
389a
391b
390a
64

FIG. 16A

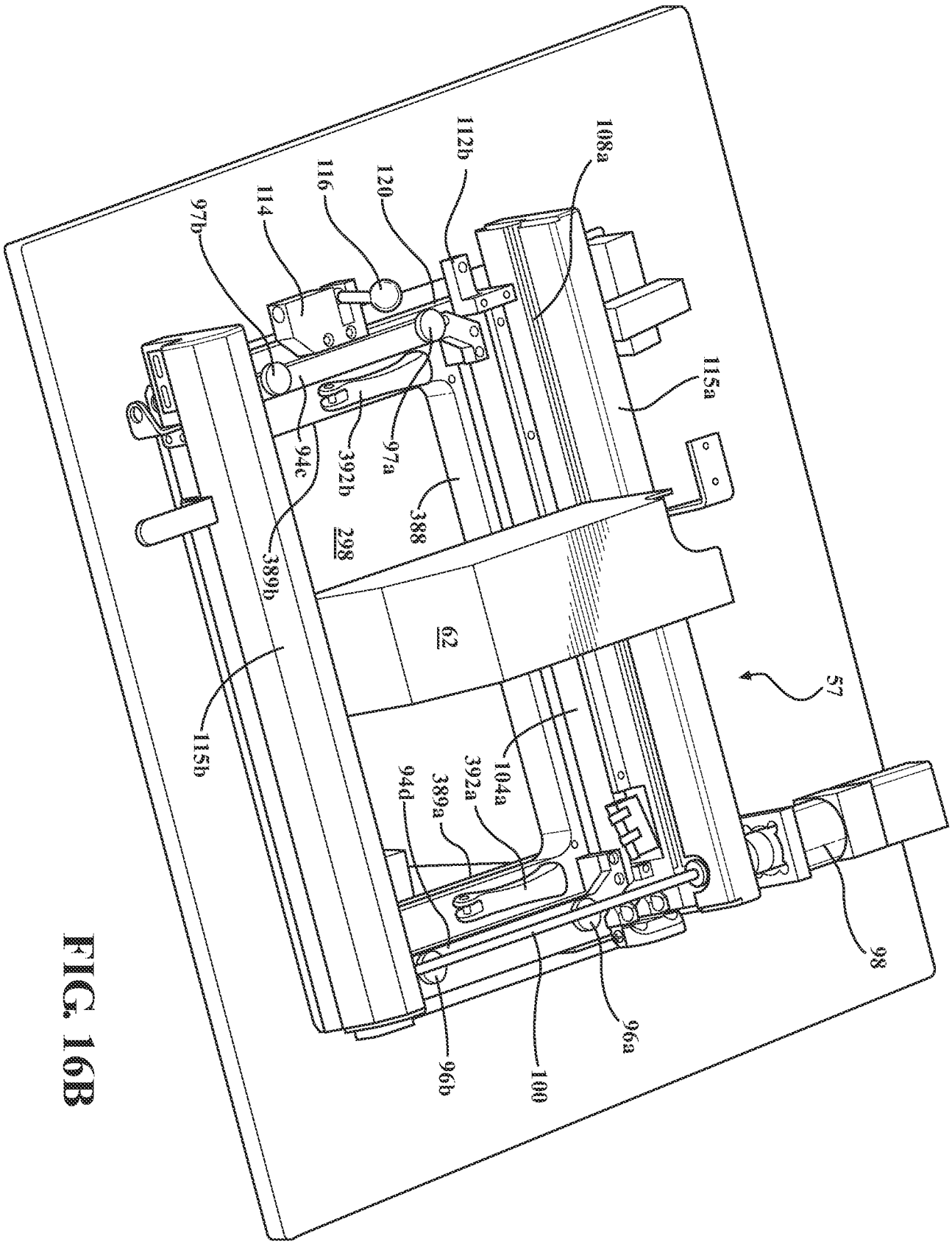

97b
114
116
120
112b
108a
115a
94c
392b
97a
388
298
389b
62
57
115b
104a
392a
389a
94d
98
96b
100
96a

FIG. 16B

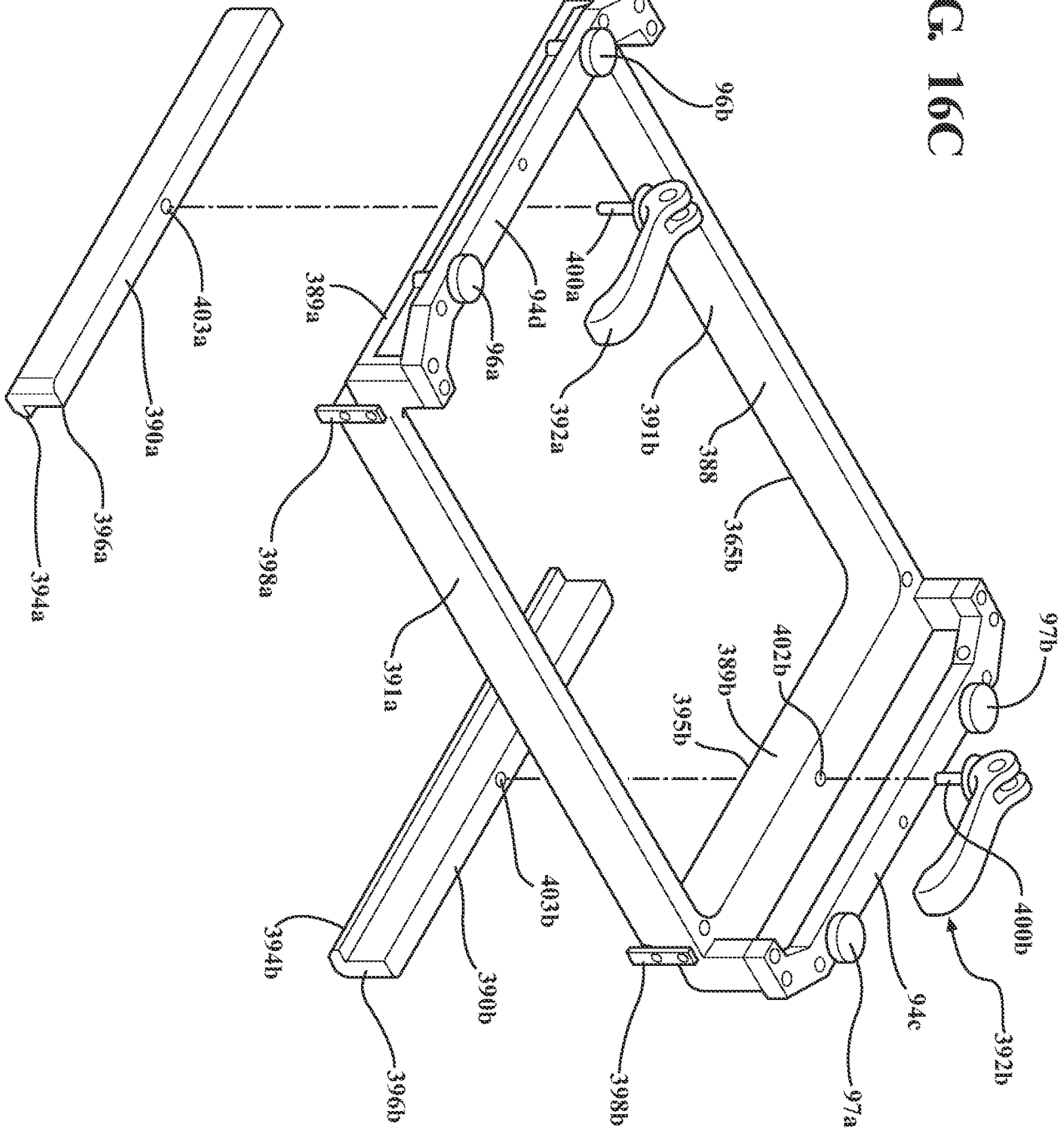

96b
403a
389a
94d
96a
400a
392a
391b
388
365b
390a
396a
394a
398a
391a
402b
389b
395b
97b
400b
403b
394b
390b
396b
398b
97a
94c
392b

FIG. 16C

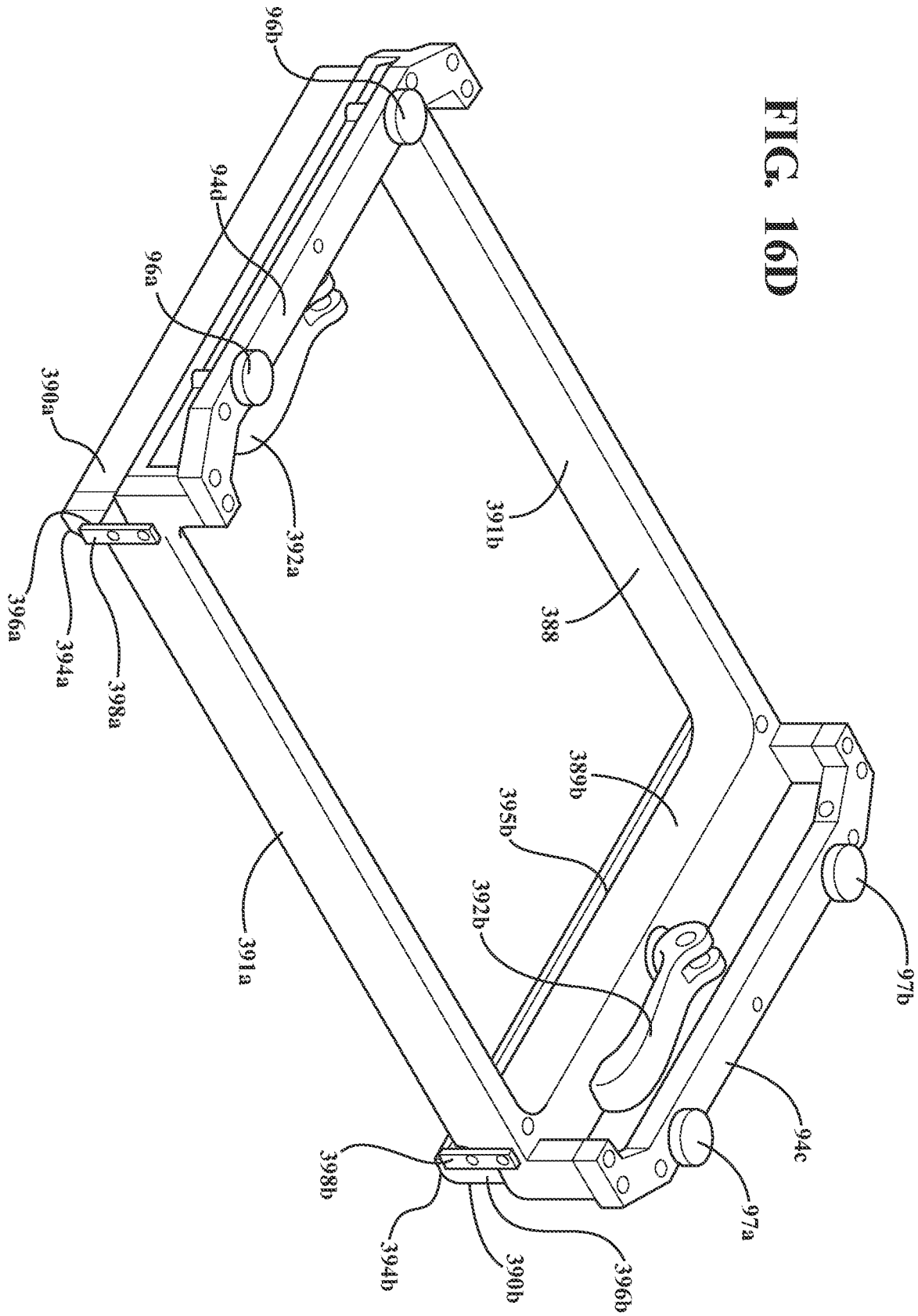

96b
94d
96a
390a
392a
391b
388
396a
394a
398a
389b
395b
392b
391a
97b
94c
398b
97a
394b
390b
396b

FIG. 16D

FIG. 16E

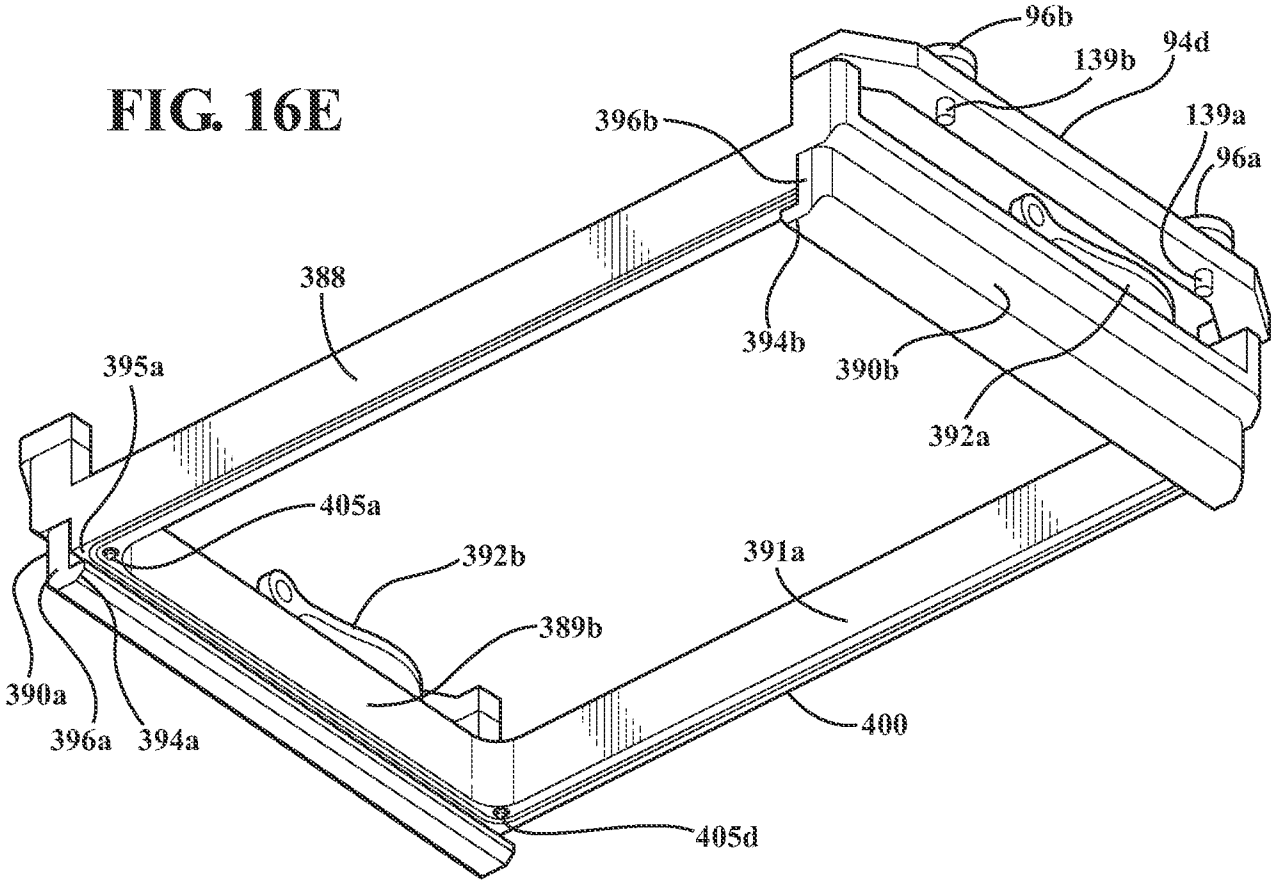
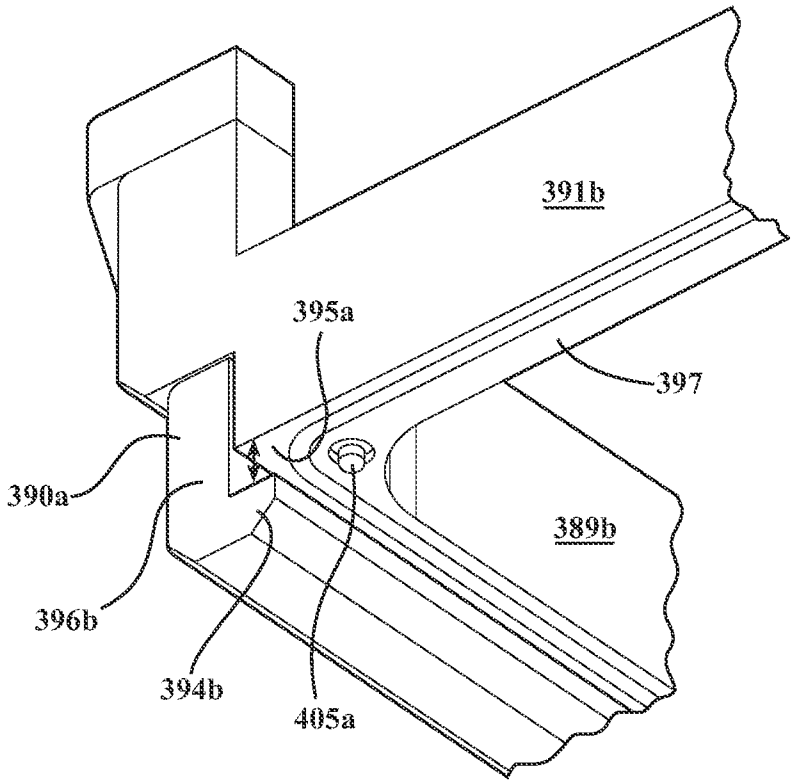


FIG. 16F



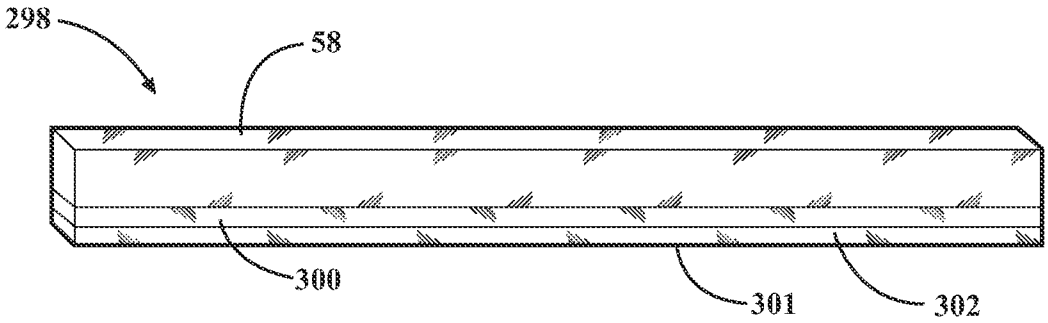


FIG. 17A

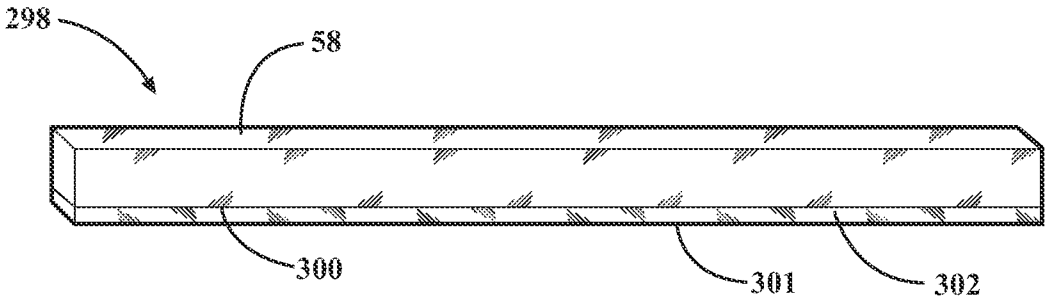


FIG. 17B

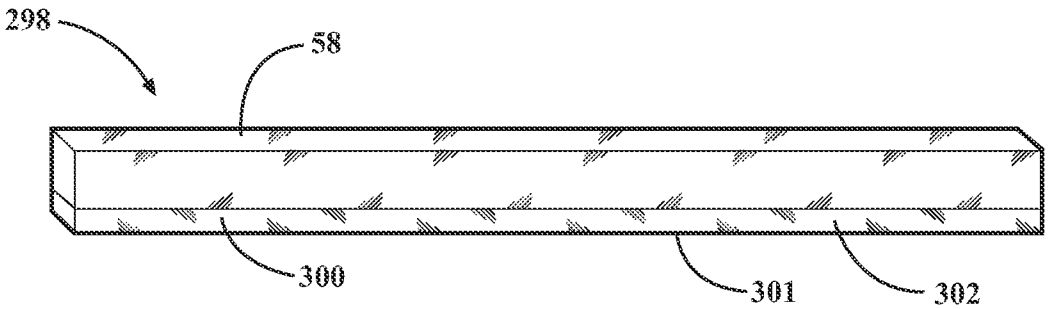


FIG. 17C

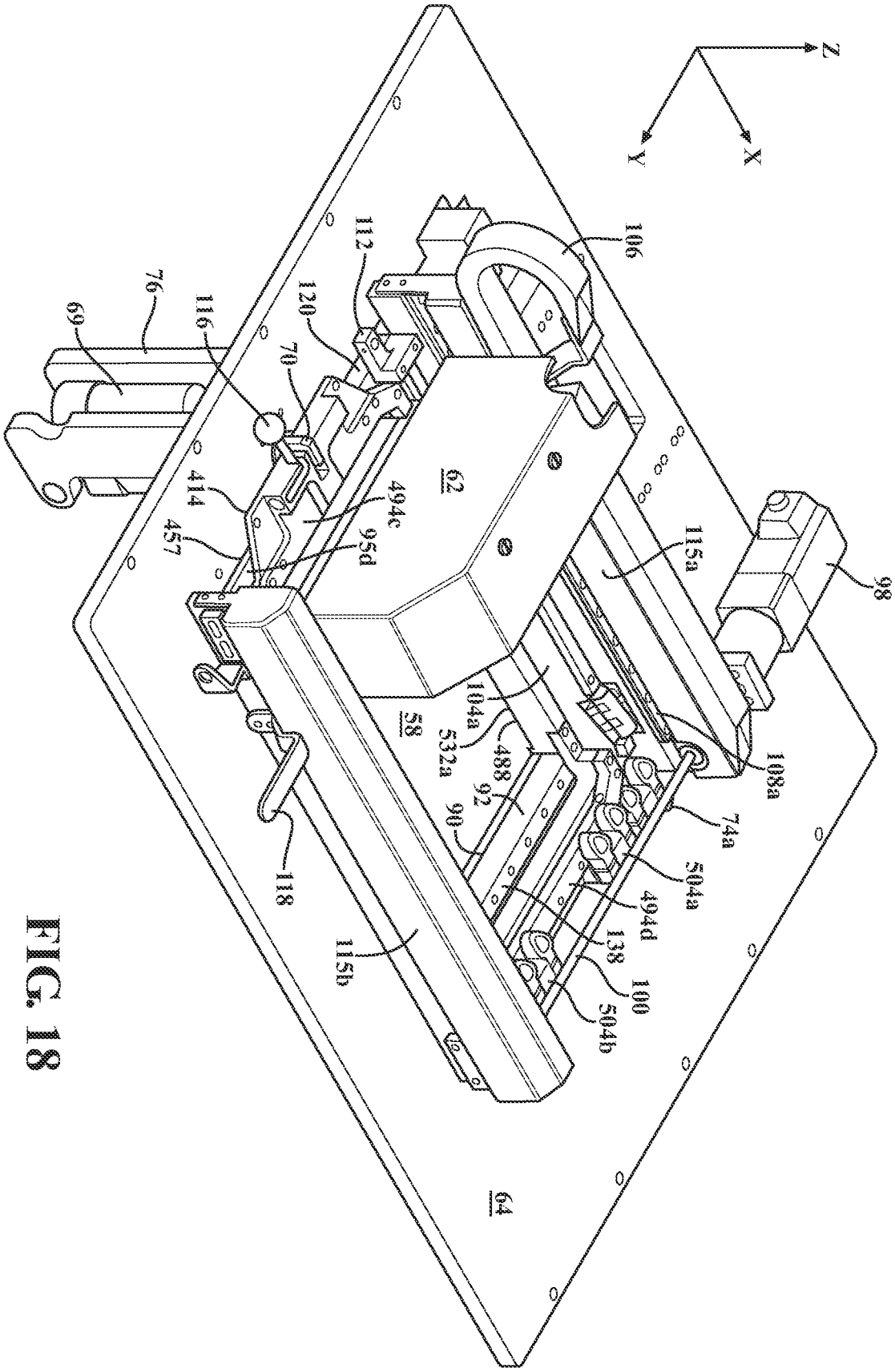

Z
Y
X
112
106
79
69
116
120
70
414
457
494c
95d
62
115a
98
104a
532a
488
92
90
58
108a
74a
504a
494d
138
100
504b
118
115b
64

FIG. 18

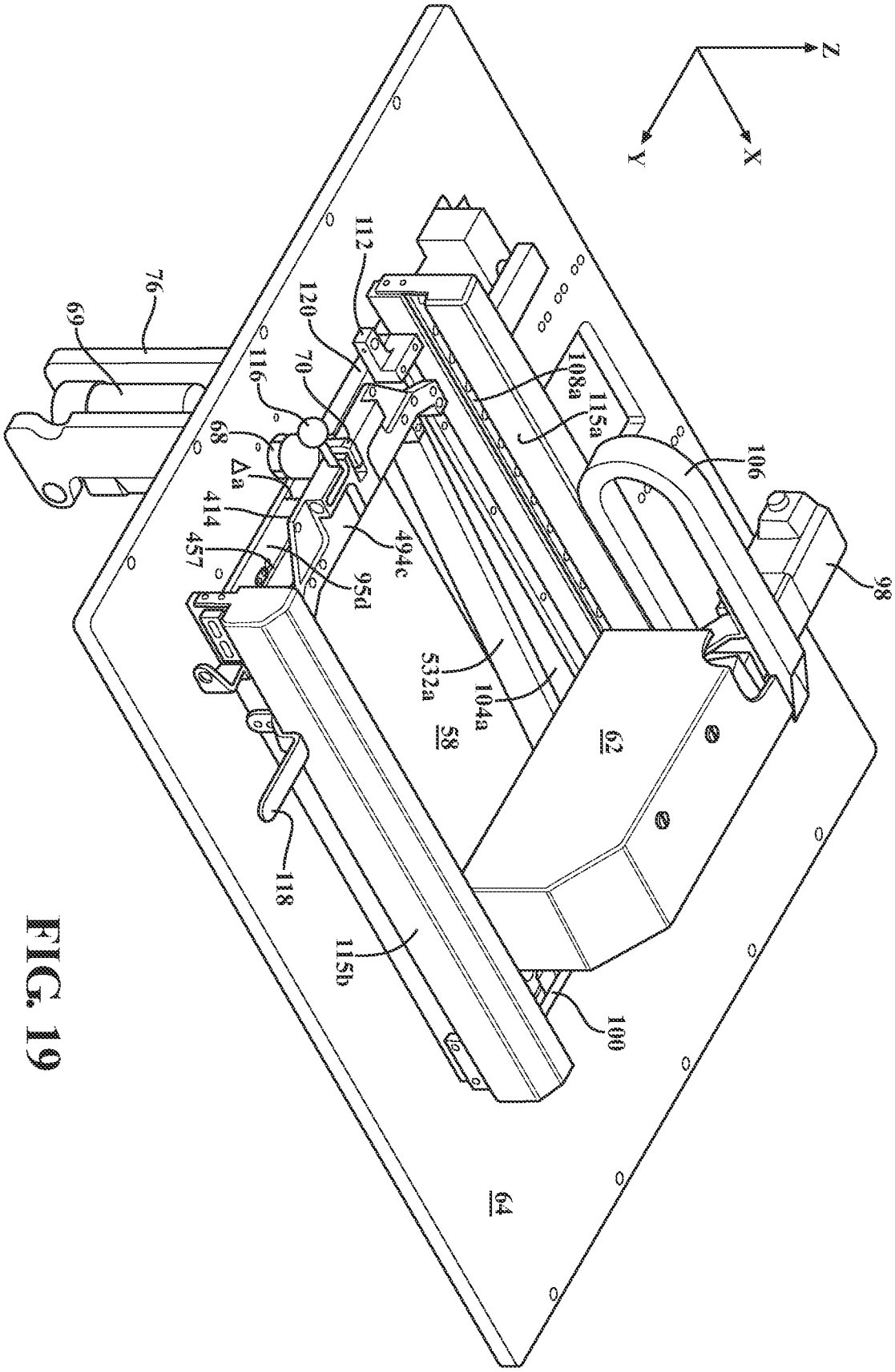

Z
Y
X
112
120
116
70
68
76
69
Δ_a
414
457
494c
95d
532a
104a
58
62
64
108a
115a
106
98
118
115b
100

FIG. 16

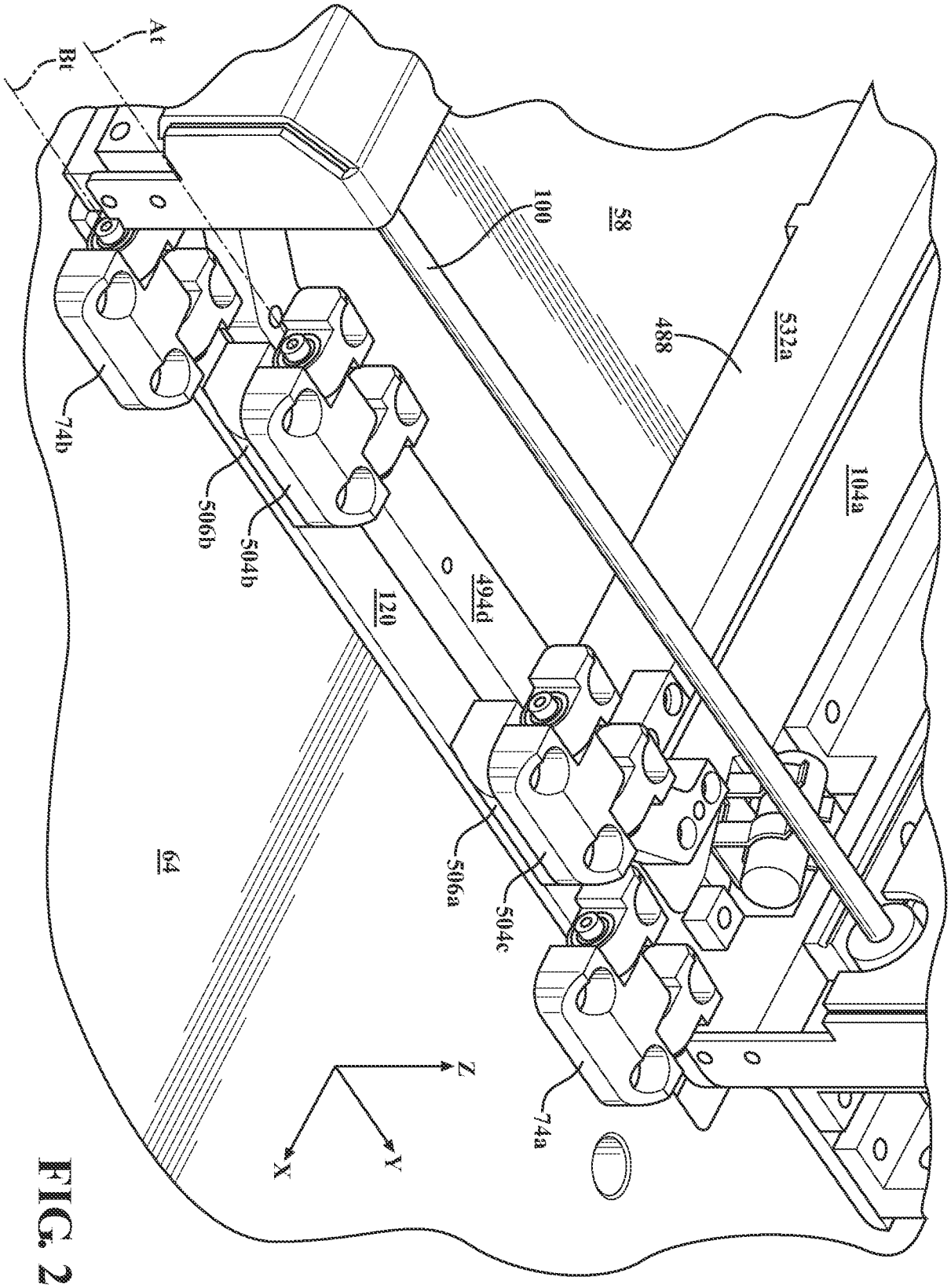

At
Bt
100
58
488
532a
74b
506b
504b
104a
494d
120
64
506a
504c
74a
Z
Y
X

FIG. 20

FIG. 21

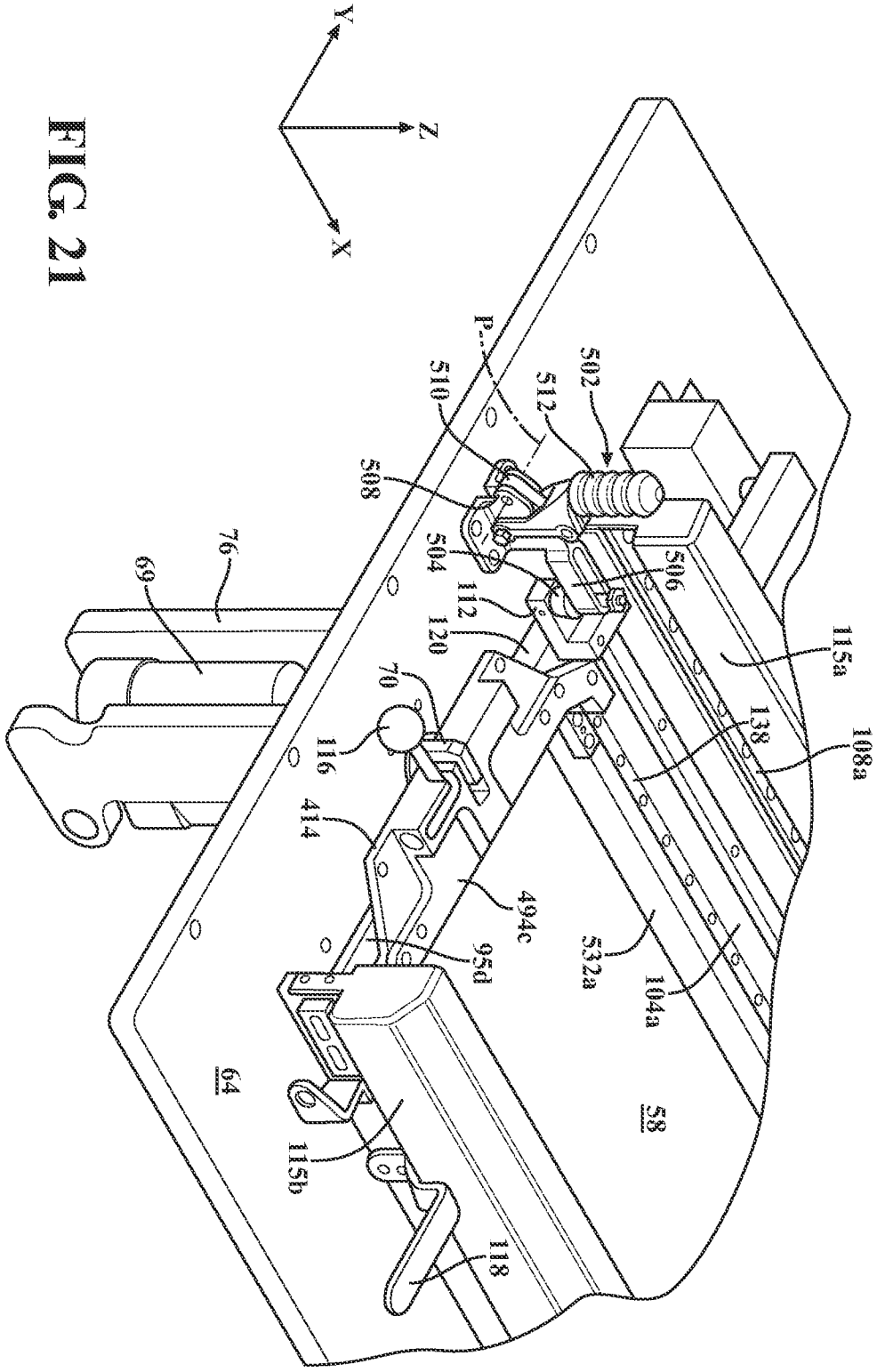
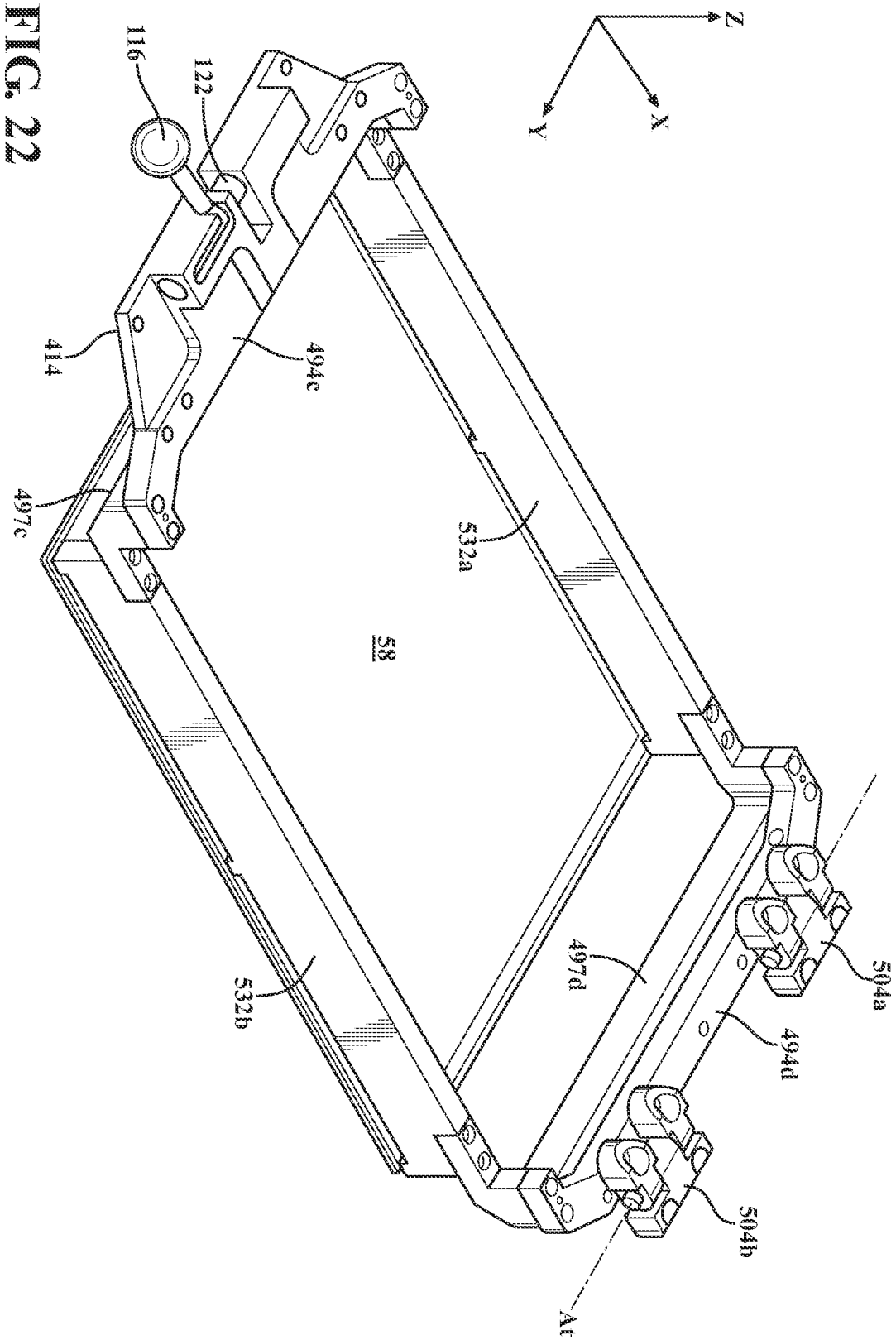

Y
Z
X
510
512
502
508
504
506
112
120
76
69
70
116
414
494c
95d
532a
104a
115a
138
108a
64
58
115b
118

FIG. 22



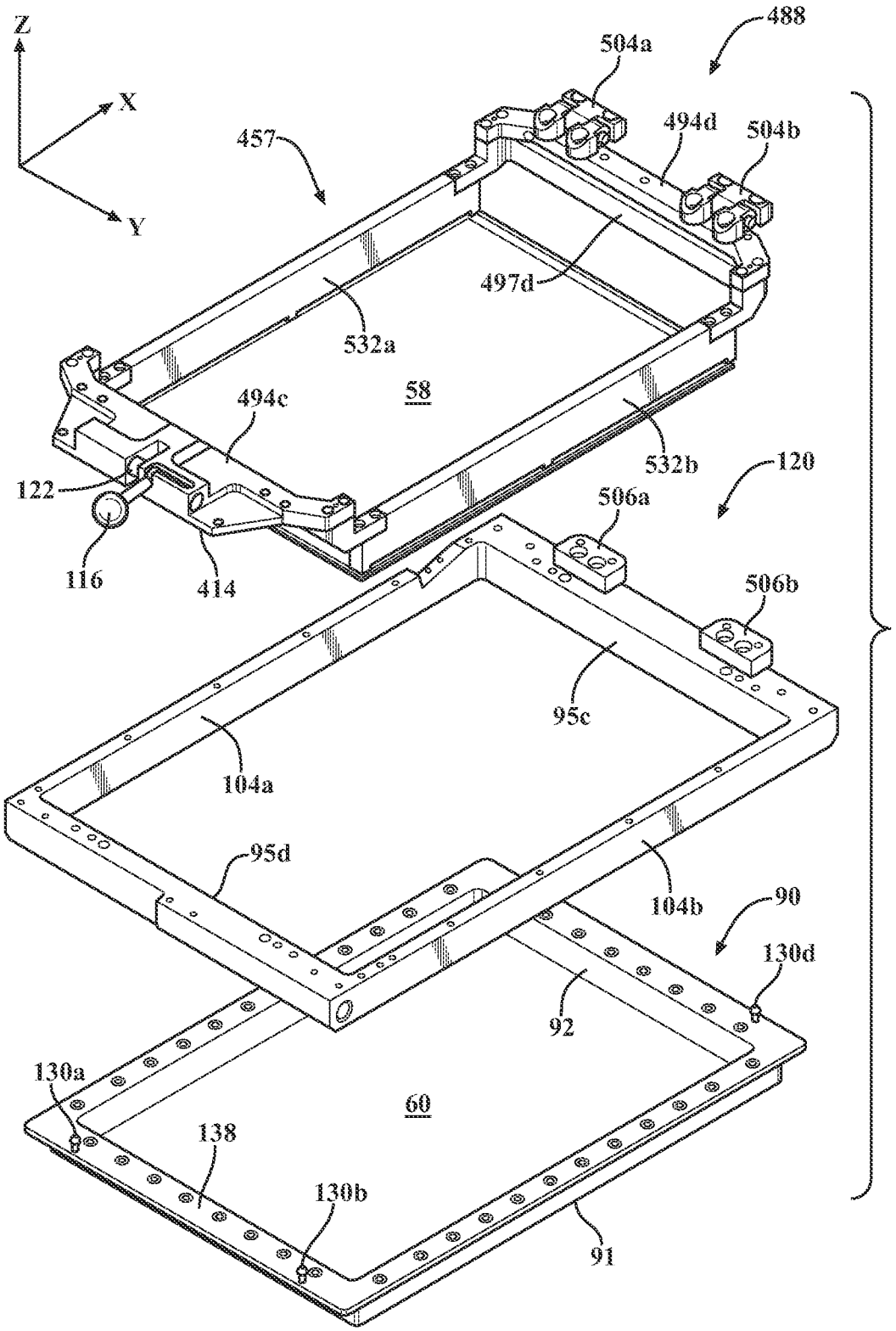

Z
X
Y
488
504a
494d
504b
457
497d
532a
58
494c
532b
120
122
506a
116
414
506b
95c
104a
95d
104b
90
130d
92
130a
60
138
130b
91

FIG. 23A

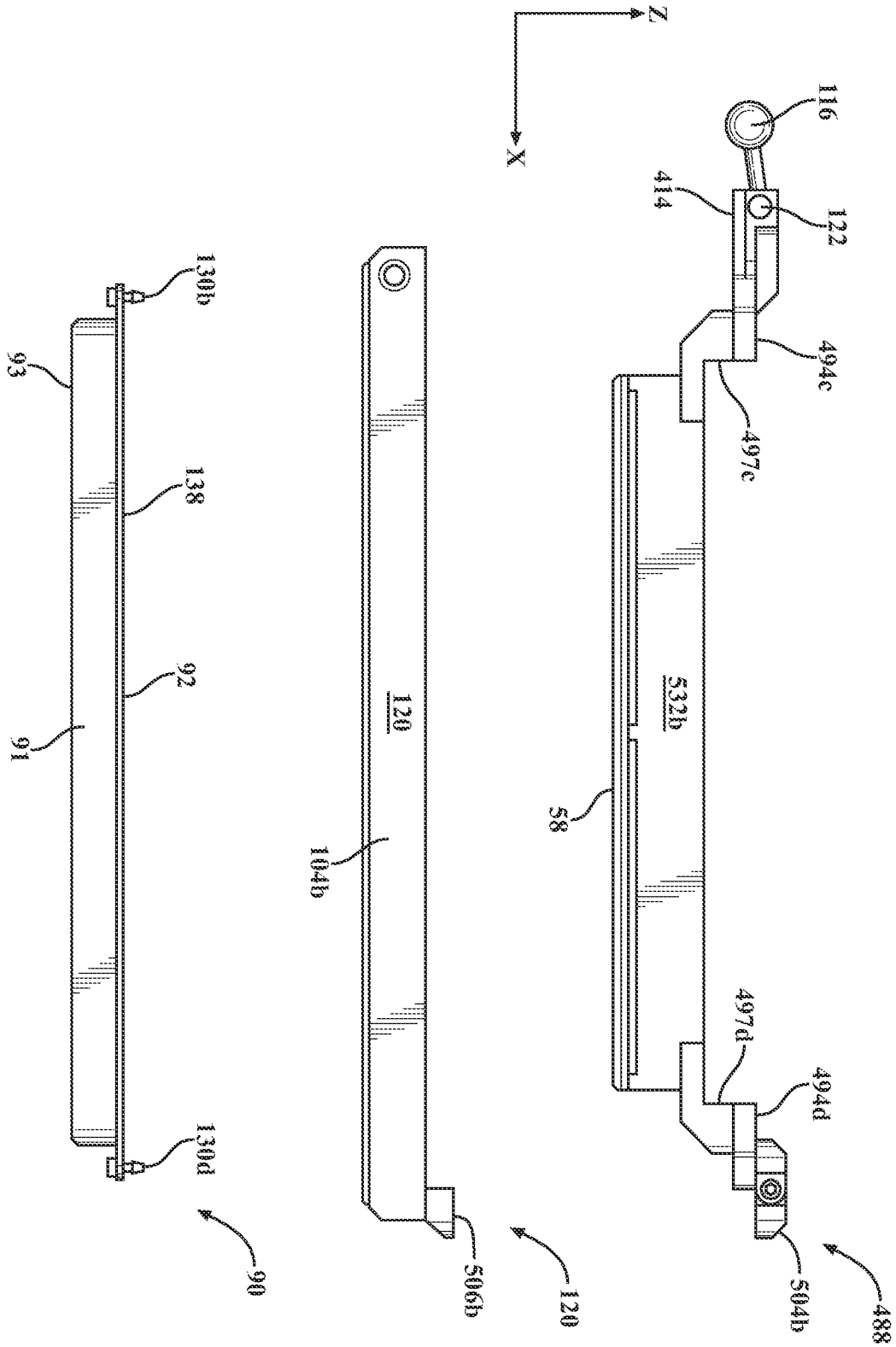

Z
X
116
414
122
494c
497c
532b
58
497d
494d
504b
488
120
506b
104b
120
130b
93
138
92
91
130d
90

FIG. 23B

FIG. 23C

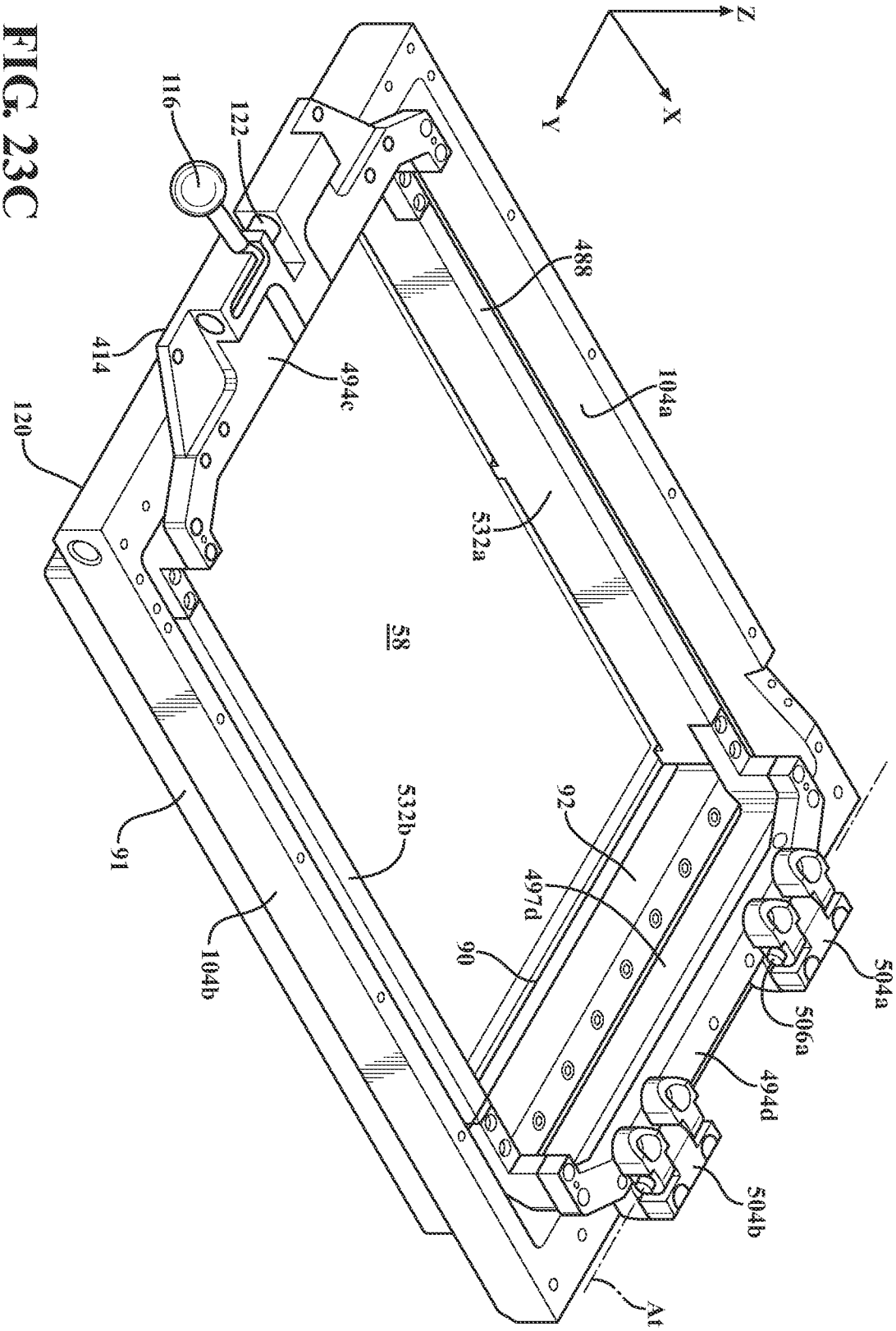
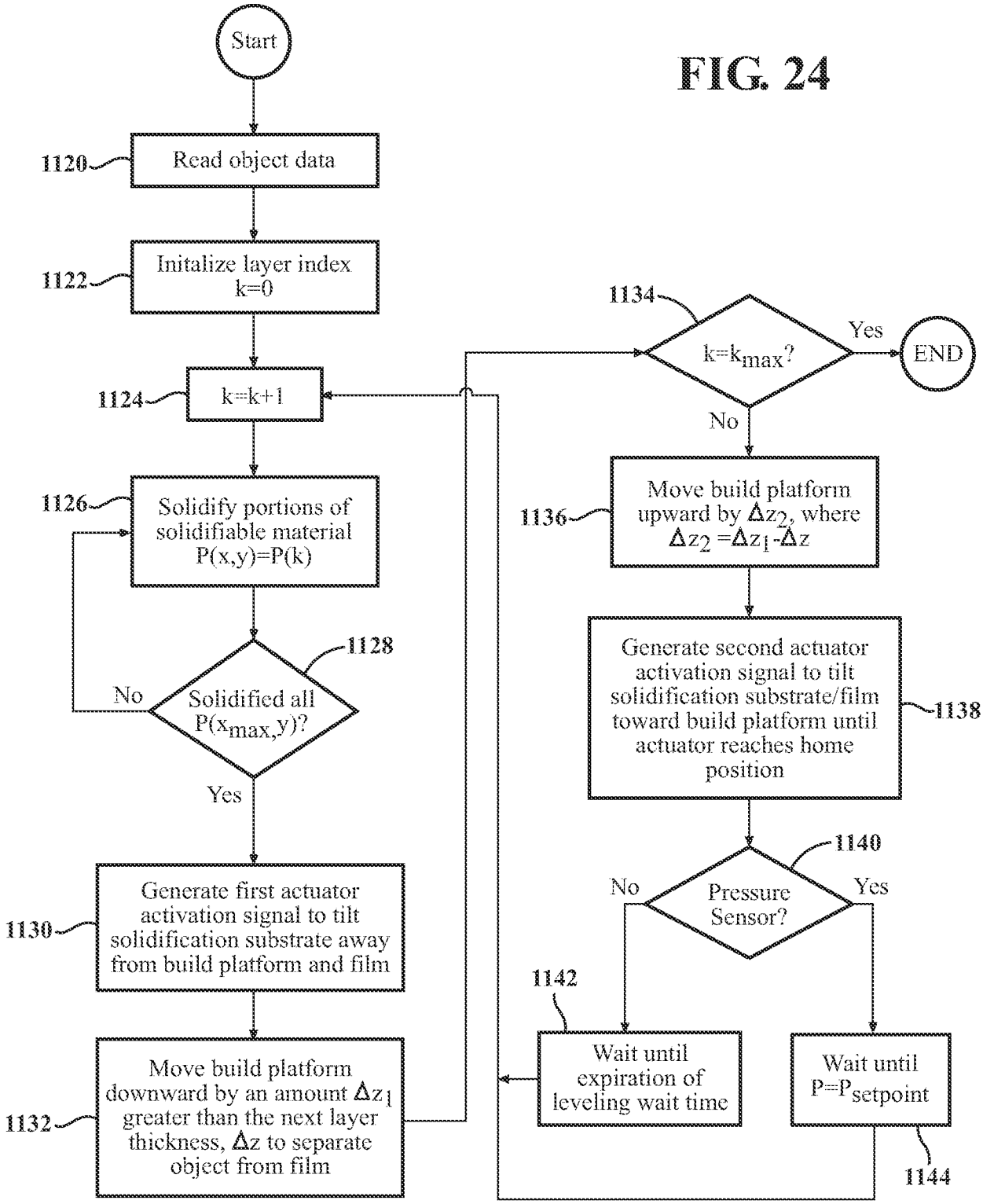

Z
Y
X
116
122
488
414
494c
104a
120
532a
58
532b
92
91
497d
90
104b
504a
506a
494d
504b
A1

FIG. 24


Start
1120
Read object data
1122
Initalize layer index k=0
1124
k=k+1
1126
Solidify portions of solidifiable material P(x,y)=P(k)
1128
Solidified all P(xmax,y)?
No
Yes
1130
Generate first actuator activation signal to tilt solidification substrate away from build platform and film
1132
Move build platform downward by an amount Δz1 greater than the next layer thickness, Δz to separate object from film
1134
k=kmax?
Yes
END
No
1136
Move build platform upward by Δz2, where Δz2 =Δz1-Δz
1138
Generate second actuator activation signal to tilt solidification substrate/film toward build platform until actuator reaches home position
1140
Pressure Sensor?
No
Yes
1142
Wait until expiration of leveling wait time
Wait until P=Psetpoint
1144

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 15/16774

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - B29C 35/08 (2015.01)
CPC - B29C 67/0062, 67/007, 67/0066, 67/0096
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8) - B29C 35/08 (2015.01)
CPC - B29C 67/0062, 67/007, 67/0066, 67/0096

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC - 425/174.4, 375; 264/401 (text search - see terms below)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PatBase; Google Scholar; Google Patents
Search Terms: three, dimension, 3D, making, build, create, solidifiable, platform, base, energy, laser, heat, film, foil, transparent, translucent, substrate, tilt, form, layer, move, lift, raise, pattern, actuator, motor, controller, computer, microcontroller, processor

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y --- A	US 2013/0001834 A1 (El-Siblani et al.) 03 January 2013 (03.01.2013), entire document especially, fig 4, 6, 8, 9B and 13, para [0052], [0059]-[0060], [0085]-[0087], [0117], [0123], [0125] and [0127]	1-3 --- 29-36 and 42-43
Y --- A	US 2013/0140741 A1 (El-Siblani et al.) 06 June 2013 (06.06.2013), entire document especially, para [0100], [0110] and [0127]	1-3 --- 29-36 and 42-43

☐ Further documents are listed in the continuation of Box C. ☐

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

Date of the actual completion of the international search	Date of mailing of the international search report
16 April 2015 (16.04.2015)	20 MAY 2015

Name and mailing address of the ISA/US	Authorized officer:
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-8300	Lee W. Young PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 15/16774

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☒ Claims Nos.: 4-28, 37-41 and 44-45
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.