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(54) **THREE DIMENSIONAL (3D) PRINTER WITH NEAR INSTANTANEOUS OBJECT PRINTING USING A PHOTO-CURING LIQUID**

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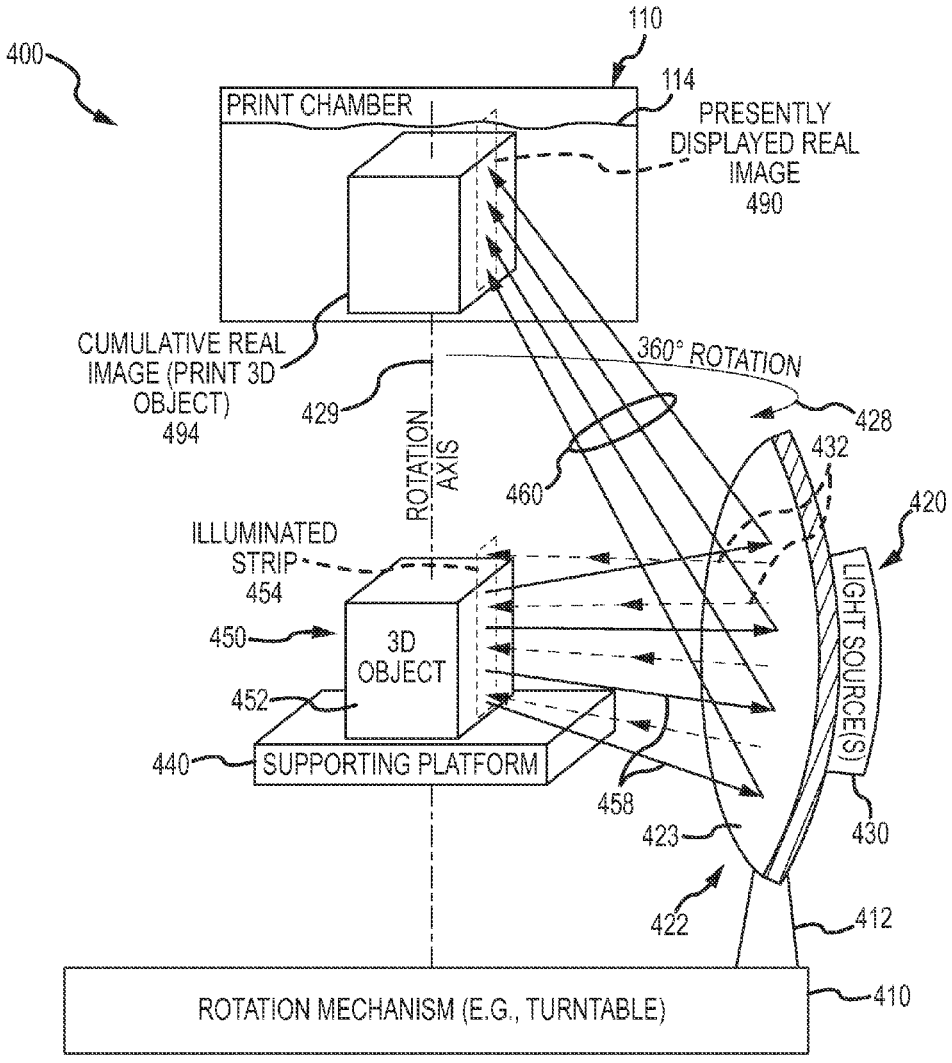
(57) **ABSTRACT**

An apparatus or three dimensional (3D) printer is provided for generating a 3D object. The apparatus includes a print chamber and a liquid print matrix such as a photo-curing resin positioned in the print chamber. The apparatus includes an optical assembly focusing light into the print chamber in the form of a real image whose light initiates curing processes for a volume of the liquid print matrix to form the 3D object. The light focused into the print chamber has a wavelength within a wavelength curing range for the photo-curing resin. The real image may be formed using an optical assembly reflecting or redirecting and focusing light reflected from outer surfaces of an existing 3D object. The real image may also be provided in the form of a volumetric image displayed by a volumetric display device displaying planes of a 3D digital model or image of a 3D object.



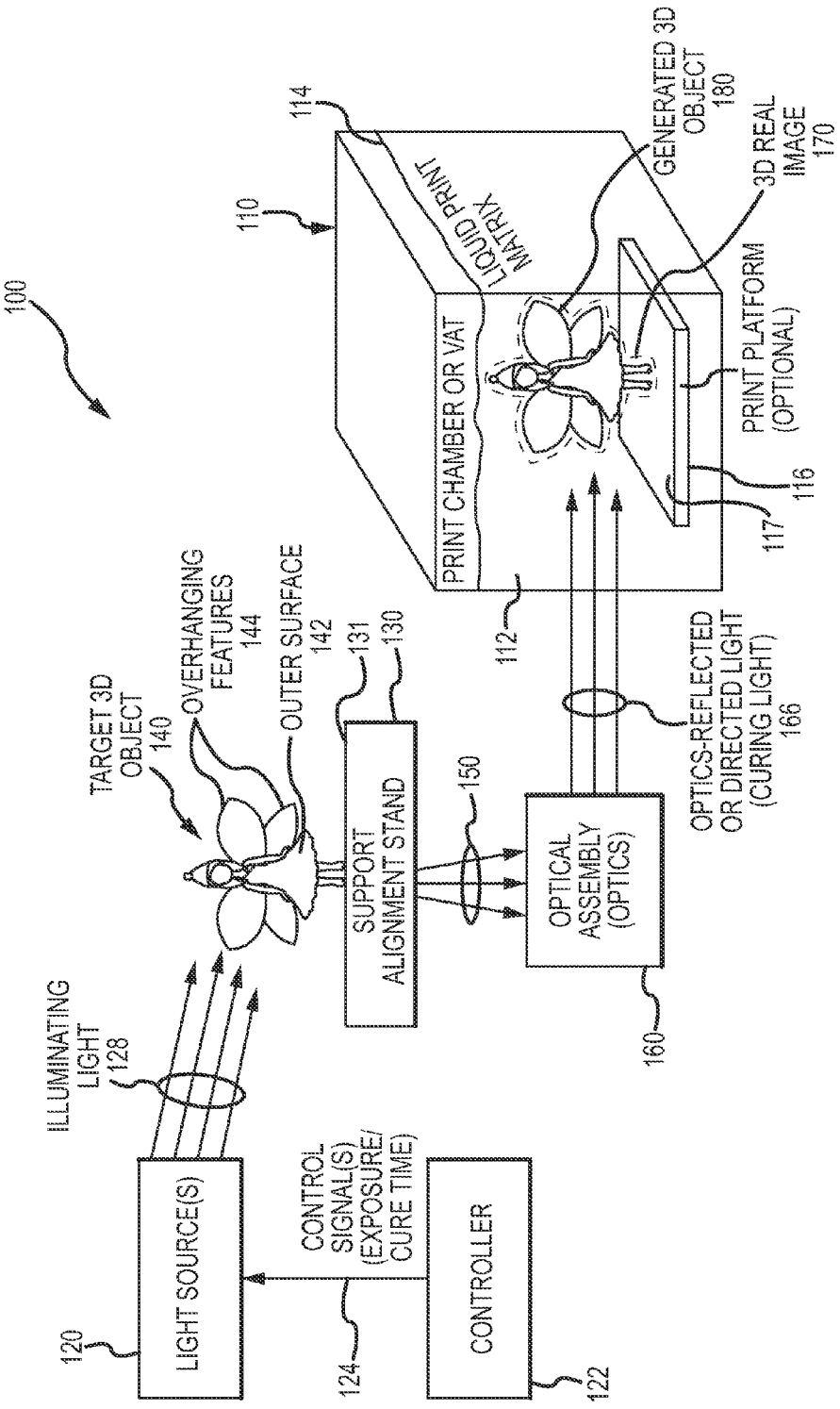

100
110
114
LIQUID PRINT MATRIX
PRINT CHAMBER OR VAT
GENERATED 3D OBJECT 180
3D REAL IMAGE 170
PRINT PLATFORM (OPTIONAL)
116
117
112
OPTICS-REFLECTED OR DIRECTED LIGHT (CURING LIGHT) 166
OPTICAL ASSEMBLY (OPTICS)
160
150
SUPPORT ALIGNMENT STAND
131
130
TARGET 3D OBJECT 140
OVERHANGING FEATURES 144
OUTER SURFACE 142
ILLUMINATING LIGHT 128
LIGHT SOURCE(S)
120
CONTROL SIGNAL(S) (EXPOSURE/ CURE TIME)
124
CONTROLLER
122

FIG. 1

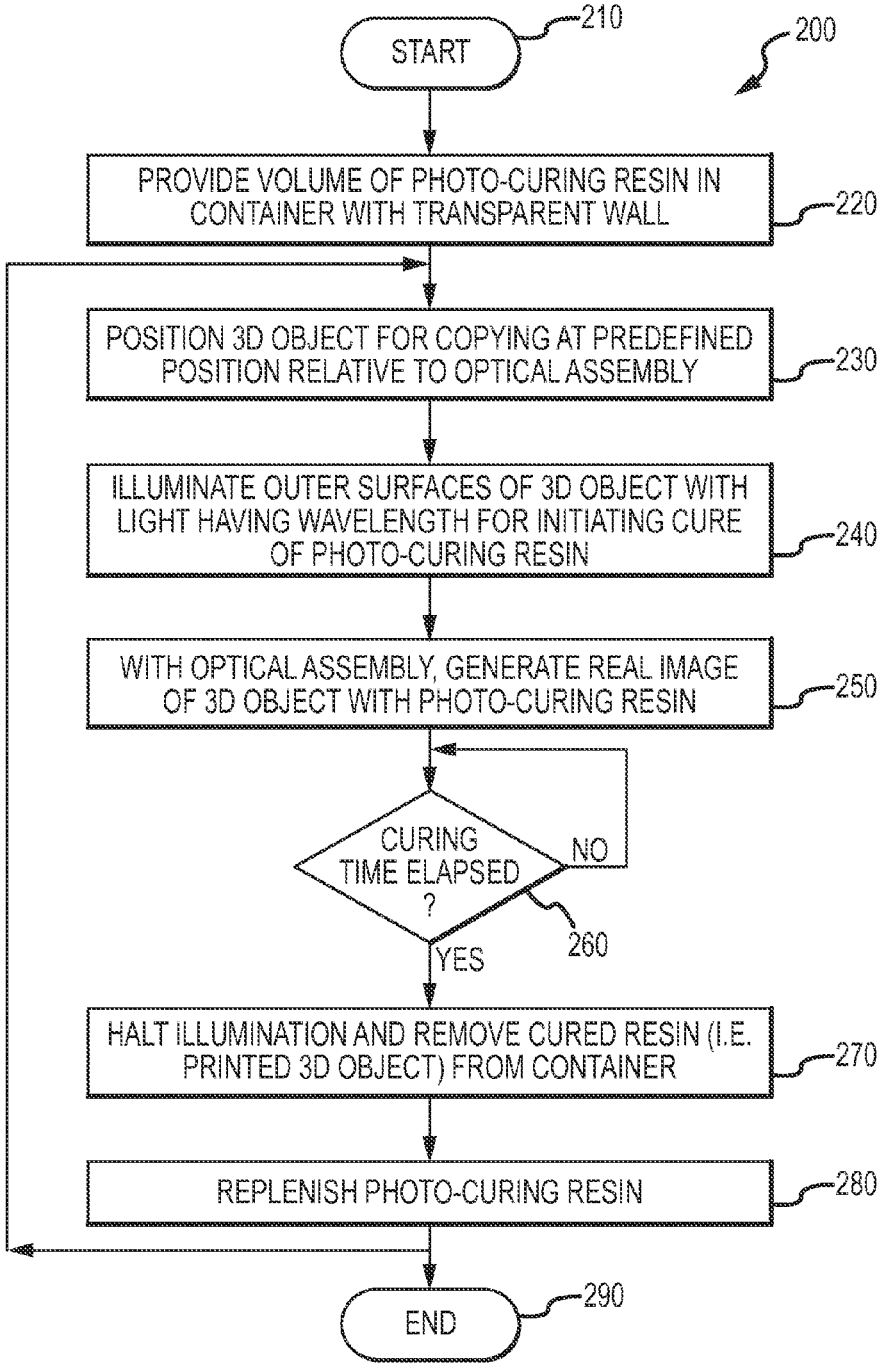

START
210
200
PROVIDE VOLUME OF PHOTO-CURING RESIN IN CONTAINER WITH TRANSPARENT WALL
220
POSITION 3D OBJECT FOR COPYING AT PREDEFINED POSITION RELATIVE TO OPTICAL ASSEMBLY
230
ILLUMINATE OUTER SURFACES OF 3D OBJECT WITH LIGHT HAVING WAVELENGTH FOR INITIATING CURE OF PHOTO-CURING RESIN
240
WITH OPTICAL ASSEMBLY, GENERATE REAL IMAGE OF 3D OBJECT WITH PHOTO-CURING RESIN
250
CURING TIME ELAPSED ?
NO
YES
260
HALT ILLUMINATION AND REMOVE CURED RESIN (I.E. PRINTED 3D OBJECT) FROM CONTAINER
270
REPLENISH PHOTO-CURING RESIN
280
END
290

FIG.2

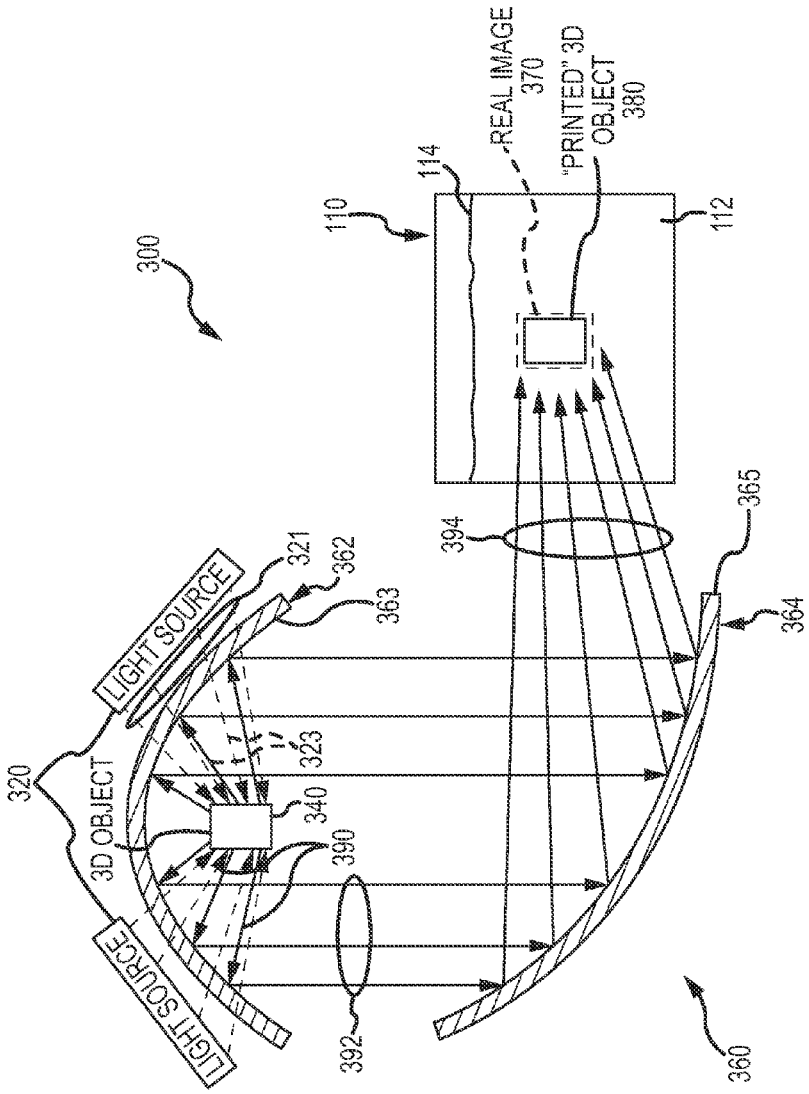

300
110
114
REAL IMAGE
370
"PRINTED" 3D
OBJECT
380
112
394
365
364
321
362
363
LIGHT SOURCE
320
3D OBJECT
323
340
390
LIGHT SOURCE
392
360

FIG.3

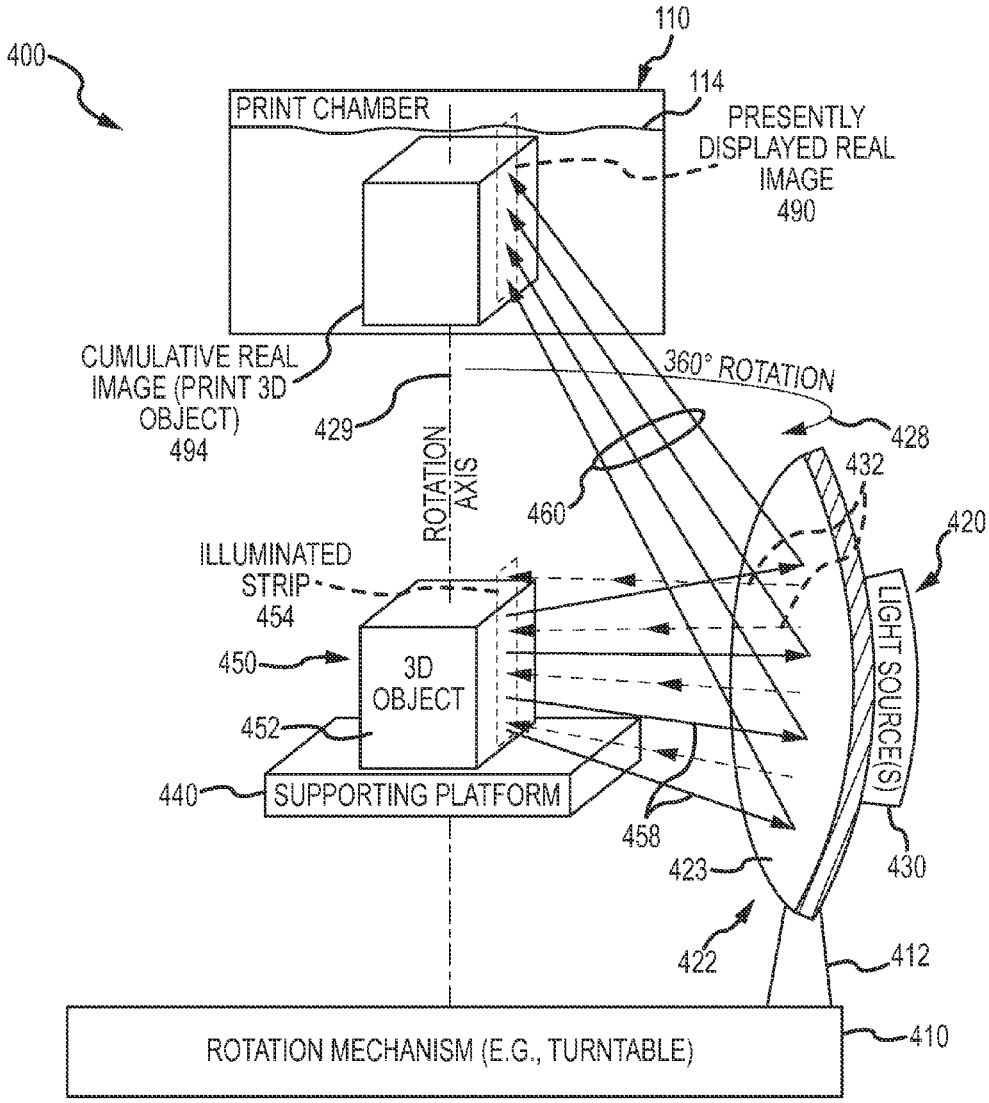

400
110
114
PRINT CHAMBER
PRESENTLY DISPLAYED REAL IMAGE 490
CUMULATIVE REAL IMAGE (PRINT 3D OBJECT) 494
429
360° ROTATION
428
ROTATION AXIS
460
432
420
ILLUMINATED STRIP 454
450
3D OBJECT
452
LIGHT SOURCE(S)
440
SUPPORTING PLATFORM
458
423
430
422
412
ROTATION MECHANISM (E.G., TURNTABLE)
410

FIG.4

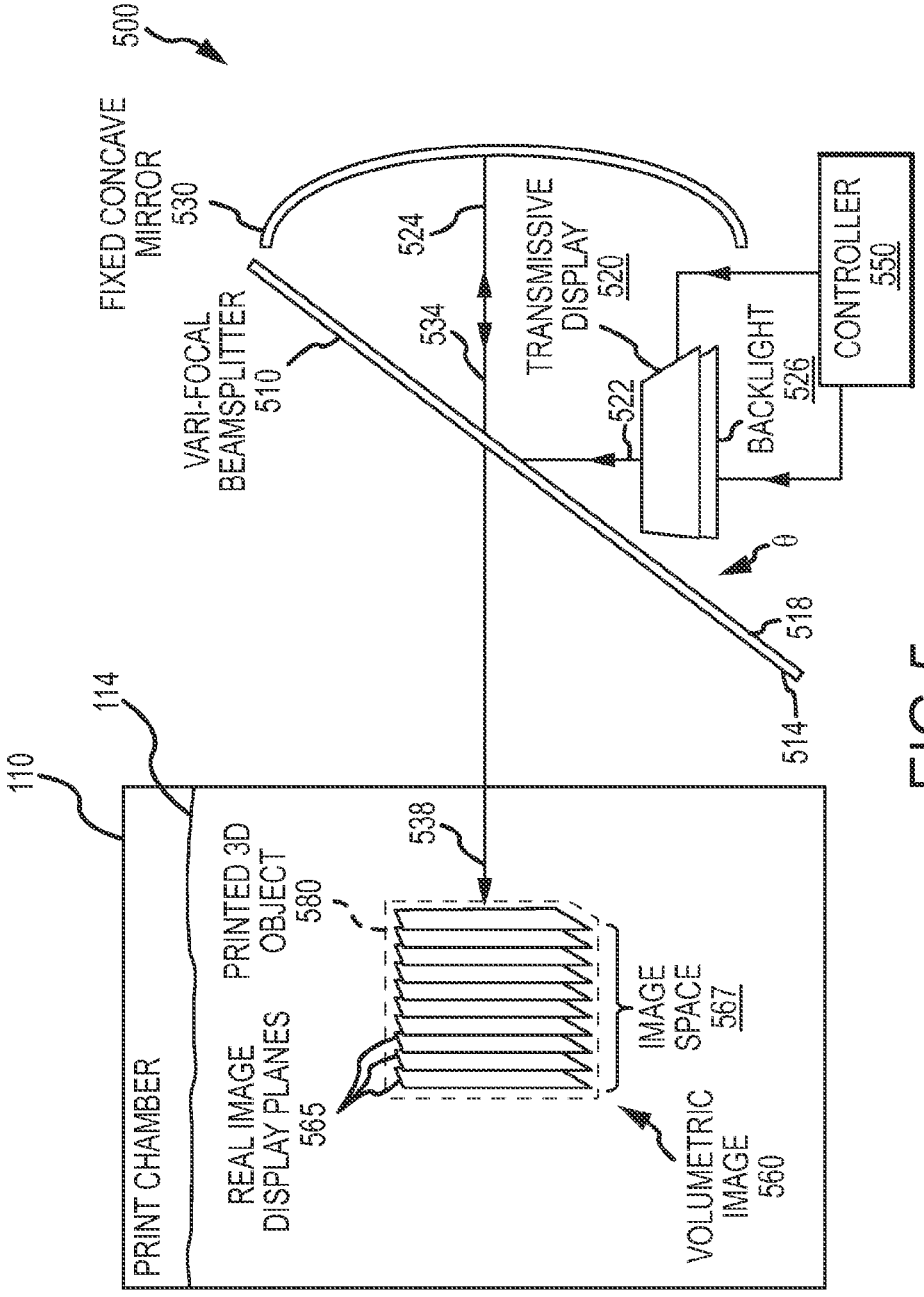

500
FIXED CONCAVE MIRROR 530
VARI-FOCAL BEAMSPLITTER 510
524
534
TRANSMISSIVE DISPLAY 520
522
BACKLIGHT 526
CONTROLLER 550
θ
518
514
110
114
PRINT CHAMBER
REAL IMAGE DISPLAY PLANES 565
PRINTED 3D OBJECT 580
538
IMAGE SPACE 567
VOLUMETRIC IMAGE 560

FIG.5

THREE DIMENSIONAL (3D) PRINTER WITH NEAR INSTANTANEOUS OBJECT PRINTING USING A PHOTO-CURING LIQUID

BACKGROUND

[0001] 1. Field of the Description

[0002] The present invention relates, in general, to fabrication of three dimensional (3D) objects, and, more particularly, to a 3D printer adapted to provide nearly instantaneous printing via selective curing of a volume or portion of a photo-curing liquid, such as a photopolymer used to provide a fluid print matrix, with the cured volume/portion corresponding to a shape defined by a digital model of a 3D object or a direct, optically transferred, real image of the 3D object.

[0003] 2. Relevant Background

[0004] Presently, 3D printing is a fabrication technology in which objects (or "printed 3D objects") are created from a digital file, which may be generated from software such as a computer aided design (CAD) program or another 3D modeling program or with a 3D scanner to copy an existing object that provides input to a 3D modeling program. To prepare the digital file for printing, software that is provided on a printer-interfacing computer or running on the 3D printer itself slices or divides the 3D model into hundreds to thousands of horizontal layers. Typically, only the outer wall or "shell" is printed to be solid such that a shell thickness may be defined as part of modifying the 3D model for use in printing. Then, during printing, the shell is printed as a solid element while the interior portions of the 3D object are printed in a honeycomb or another infill design, e.g., to reduce the amount of material that has to be printed to provide the printed 3D object.

[0005] When the prepared digital file of the 3D object is uploaded into the 3D printer, the 3D printer creates or prints the object layer-by-layer. The 3D printer reads every slice (or 2D image) from the 3D model and proceeds to create the 3D object by laying down (or printing) successive layers of material until the entire object is created. Each of these layers can be seen as a thinly sliced horizontal cross section of the eventually completed or printed 3D object,

[0006] One of the more common 3D printer technologies uses fused deposition modeling (FDM) or, more generally, fused filament fabrication (FFF). FDM printers work by using a plastic filament (e.g., acrylonitrile butadiene styrene (ABS) or polylactic acid (PLA) provided as strands of filament that is 1 to 3 millimeters in diameter) that is unwound from a spool mounted onto the printer housing. The plastic filament is used to supply material to a print head with an extrusion nozzle, e.g., a gear pulls the filament off the spool and into the extrusion nozzle. The extrusion nozzle is adapted to turn its flow on and off. The extrusion nozzle (or an upstream portion of the print head) is heated to melt the plastic filament as it is passed into the extrusion nozzle so that it liquefies. The extrusion nozzle deposits the liquefied material in ultra fine lines, e.g., in lines that are about 0.1 millimeters across.

[0007] The extrusion head and its outlet are moved, in both horizontal and vertical directions to complete or print each layer of the 3D model, by a numerically controlled mechanism that is operated by control software running on the 3D printer, e.g., a computer-aided manufacturing (CAM) software package adapted for use with the 3D printer. The extruded melted or liquefied material quickly solidifies to form a layer (and to seal together layers of the 3D object), and the extrusion nozzle is then moved vertically prior to starting the printing of the next layer. This process is repeated until all layers of the 3D object have been printed.

[0008] Presently, 3D printing is extremely slow and time consuming. For example, it may take several hours to print a single 3D object even if the 3D object is relatively small (e.g., a 3D object that is only several inches in diameter and four to twelve inches tall). The 3D printing process that uses conventional 3D printers such as an FFF-based 3D printer is limited in its speed by the speed of the mechanism moving the print heads to each new position on a print layer. Hence, there remains a need for 3D printing methods, and 3D printers that implement such methods, that can generate a 3D object with increased speed while retaining or even improving on the quality of the 3D object.

[0009] A further problem with existing 3D printing techniques is the need for printing a support structure for any overhanging components of a 3D object. For example, a figurine of a human-like character may have its arms extending outward from its body or torso, and the arms would be cantilevered out from the body or overhang from the adjacent portions of the body. A support structure would have to be included in layers printed below or in advance of the overhanging components or portions of the 3D object to provide material upon which to print the overhanging components. This slows the printing process further as a significant amount of material may have to be printed to provide the support structure. Upon completion of printing, the 3D object requires finishing including removal of the support structure and, in some cases, sanding or polishing of the surfaces from which the support structure was removed to match the finish of adjacent surfaces. These additional steps also increase the production time of the 3D object and typically must be performed manually, which further increases fabrication costs and complexities. Hence, it would be desirable to provide a 3D printing method, and associated 3D printer, that can "print" a 3D object without the need for support structures for overhanging or cantilevered features.

SUMMARY

[0010] Briefly, a 3D printer (and corresponding 3D print method) is described that is adapted for "printing" or generating a 3D object in a manner that circumvents the layer-by-layer approach of conventional 3D printers that has significantly limited achievable printing speeds. In one design approach, the 3D printer is configured with the assumption that a physical "original" of a 3D object already exists (not just a digital model of a 3D object). In this first 3D printer design, the 3D printer acts as a high speed 3D copying machine because it uses an optical assembly or a set of optics that relays a volumetric real image (versus a virtual image) of the existing or target 3D object into a vat or container holding a volume of a photo-curing liquid or resin (e.g., a photopolymer or photo-cure liquid polymer).

[0011] The light associated with the volumetric real image, which is provided by one or more light sources directing light onto the existing or target 3D object, causes a portion or volume of the photo-curing liquid to be cured in a nearly instantaneous manner to generate or produce the entire 3D object (rather than slowly and layer-by-layer as with conventional 3D printers). The printed or produced 3D object, which is floating in or supported in the uncured liquid (e.g., a resin selected to be translucent to transparent to light and also viscous to support the in-process 3D object), can simply be lifted out of the vat/container. In several testing operations, a

3D printer using photo-curing liquids has been proven effective in generating 3D objects in several minutes or less rather than in several hours.

[0012] More particularly, an apparatus or 3D printer is provided for generating (or "printing" in a nearly instantaneous manner) a physical three dimensional (3D) object. The apparatus includes a print chamber with one or more sidewalls enclosing an interior void adapted for containing liquids, and a liquid print matrix (such as a photo-curing resin or liquid, which may be a photopolymer or the like) positioned in the interior void of the print chamber. The apparatus includes an optical assembly operating to focus light into the interior void of the print chamber to initiate curing processes for a volume of the liquid print matrix to form a 3D object. The light focused into the print chamber has a wavelength within a wavelength curing range for the photo-curing resin.

[0013] In some cases, the photo-curing resin is transmissive (e.g., translucent to transparent) of light having a wavelength in the wavelength curing range when in liquid form and when in hardened form. In the same or other embodiments, the photo-curing resin has a first specific gravity in a liquid form and a second specific gravity when cured, and the second specific gravity may be in a range of 90 to 110 percent of the first specific gravity. In this way, the formed 3D object is supported by adjacent uncured portions of the photo-curing resin in the print chamber, and no supporting structure has to be printed for cantilevered or overhanging object features (such as arms of a figurine).

[0014] In some embodiments of the apparatus, the light focused into the print chamber displays or provides a real image defining at least an outer shell of the 3D object. In these cases, the apparatus may include a light source illuminating outer surfaces of a target 3D object, and the optical assembly may include a first curved mirror receiving and reflecting light reflected from the outer surfaces of the target 3D object and further include a second curved mirror receiving and reflecting the light reflected from the first curved mirror as the light focused into the print chamber. The curved mirrors may be parabolic mirrors or reflectors to implement the apparatus.

[0015] In other implementations, the optical assembly may include a curved mirror, a light source directing light through the curved mirror, and a rotation mechanism rotating the curved mirror and the light source along a circular path about a target 3D object. In such an apparatus, the light source illuminates a plurality of vertical strips or lines of outer surfaces of the target 3D object as the light source and the curved mirror are moved along the circular path (e.g., to provide circumferential scanning). The curved mirror is configured to reflect light reflected from the outer surfaces of the target 3D object to provide the light focused into the print chamber, e.g., to provide a plurality of real image strips or slits of light that accumulate in the print chamber to provide a 3D real image of the target or existing 3D object being copied by operation of the apparatus.

[0016] Alternatives to curved mirrors may include refractive optical systems, which can include focusing lenses that are able to generate a real image of the object, or portions of the object, to be copied and are also able to focus it into the print chamber. It should be understood that although the attached figures illustrate embodiments using curved mirrors the analogous optical function accomplished with focusing lenses may be applied to successfully practice the invention (s) described herein.

[0017] In some embodiments of the apparatus or 3D printer, the real image displayed in the print chamber or vat is a volumetric image displayed by a volumetric display device. In such embodiments, the volumetric image can be defined by a 3D digital model that includes numerous frames used to sequentially display a plurality of real image display planes (or slices or layers of the overall 3D real image) in an image space coinciding with the interior void of the print chamber. This causes near-concurrent curing of a plurality of layers or planes within the liquid print matrix contained in the print chamber to form or print the 3D object.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] FIG. **1** is a functional block diagram of a 3D printer (or 3D object generation system) during its use or operation to print or create a 3D object;

[0019] FIG. **2** is a flow diagram for a method of fabricating or printing a 3D object using a 3D printer of the present description such as the printer or object generation system of FIG. **1**;

[0020] FIG. **3** is a side sectional and schematic view of a 3D printer with one exemplary optical assembly of the present description for providing a real image within a print chamber or vat of photo-curing resin;

[0021] FIG. **4** is a functional block view showing another 3D printer using an optical assembly including a rotating curved mirror to provide real images in a vat of photo-curing resin; and

[0022] FIG. **5** is a functional block drawing of a 3D printer using a volumetric display device to display a volumetric image in a volume of photo-curing resin in a print chamber or vat to form a 3D object.

DETAILED DESCRIPTION

[0023] The inventors recognized that existing or conventional 3D printers, such as FFF-based 3D printers, are extremely slow in printing a 3D object. Further, conventional 3D printers require that support structure must be printed for any overhanging portions of the 3D object, which further slows the printing process and requires post-printing fabrication steps to remove the support structure. To address these and other issues with conventional 3D printers, a 3D printer (or 3D object generation system) is taught herein that, instead of building up an object by creating successive layers, builds or forms a 3D object by concurrently curing a volume or portion of a photo-curing liquid (e.g., a photopolymer resin).

[0024] In some embodiments, an existing 3D object is copied, and the 3D printer includes a light source for illuminating the existing 3D object and an optical assembly for generating (reflecting and/or redirecting light) a real image from light reflected from the 3D object. The light corresponding to the real image is directed into a print chamber or vat of the photo-curing liquid (and this volume may be thought of as a liquid print matrix) for a time falling within a curing range for the photo-curing liquid, which is usually a relatively short time such as several minutes or less to provide nearly instantaneous "printing" or forming of a 3D object in the print chamber. The cured volume of the photo-cure liquid may correspond with the outer surfaces of the target or existing 3D object so as to provide a solid outer shell (e.g., a hollow 3D object is printed).

[0025] In other embodiments, a volumetric image is projected or displayed within the photo-curing liquid or resin of

the print chamber using a real image source, which may provide spatially offset frames defining a 3D image or volumetric image of a target 3D object. For example, a volumetric display device may be used to provide the light used to cure the photo-curing resin ("the curing light"), and, in this way, an outer shell may be formed or printed and, optionally, an internal structure or in-fill may also be formed. These embodiments of the 3D printer (and associated 3D print methods) may be used to create things that are not in the physical world or are not available for scanning or copying, and the 3D printers may be used to provide internal features/elements that cannot be copied by illuminating outer surfaces of an existing 3D object.

[0026] FIG. **1** is a functional block diagram of a 3D printer or 3D object generation system **100** during printing or building operations to create a 3D object **180**. As shown, the 3D printer **100** includes a print chamber or vat (or container) **110** with one or more sidewalls **112** that are adapted to contain a volume of a photo-curable resin (or a liquid print matrix) **114**, e.g., a volume that is greater than a volume of cured material required to obtain the generated 3D object **180**. The print chamber **110** may be rectangular in shape as shown or take another form such as a cylinder. The sidewalls **112** (or at least one sidewall) is transparent (or substantially so) to light to allow curing light **166** to be directed into a plurality of depths in the liquid print matrix **114** to allow light with sufficient brightness or energy to be provided in the interior void of the print chamber to cure a portion or volume of the matrix **114** to create the 3D object **180**.

[0027] The liquid print matrix **114** may take a plurality of forms to practice the 3D printer **100**. Generally, the liquid print matrix **114** is made up of a liquid that is light transmissive to allow a real image **170** to be created within the chamber **110** via light of a particular wavelength or energy. In some embodiments, the liquid used for the print matrix **114** is also chosen to have a minimum viscosity such that uncured portions of the liquid print matrix **114** function to support portions of the 3D object **180** as they are being formed or "printed" including any cantilevered or overhanging elements (e.g., overhanging features **144** on the target 3D object **140**). In some cases, a print platform **116** is provided in the chamber **110**, and its upper surface **117** is used to support lower portions of the 3D object **180** as it is being formed by curing a portion or a volume of the liquid print matrix **114**. In some embodiments, the matrix **114** is provided by placing a volume of a photopolymer or other photo-curing resin or liquid into the print chamber or vat **110**.

[0028] Prior to turning to other components of the 3D printer, it may be useful to discuss more generally the process of curing the print matrix **114** to form a 3D object **180**. In a first approach, the 3D object **180** is generated by curing a subset or portion (or a volume) of the liquid print matrix **114** by projecting or displaying a 3D real image **170** in the vat **110**. To this end, particular properties are preferred for the photo-curing resin used to provide the liquid print matrix **114**. The resin can contain photoinitiators that absorb a certain wavelength of light, which initiates a crosslinking or polymerization process to happen where the real image is the brightest (e.g., outer surface of the 3D real image **170**). This causes the polymer to physically harden or to be cured.

[0029] The resin can cure at either a visible or invisible wavelength. This depends on the wavelength absorbed by the photoinitiator. In prototype testing of a 3D printer like the one shown in FIG. **1** at **100**, the inventors cured photo-curing resin using blue light (wavelength of approximately 450 nm), violet light (wavelength of approximately 405 nm), and ultraviolet light (wavelength of approximately 365 nm). Resins that cure with invisible wavelengths are less affected by ambient light, which may make them useful in some 3D printers **100**.

[0030] The resin tbr print matrix **114** should be selected to both absorb and transmit light (be transmissive) at the curing wavelength. Higher absorption results in a faster rate of curing, but it also provides a shorter maximal curing depth in the print chamber **110**. The maximal curing depth determines the size of the largest object that can be cured. Higher transmission results in a slower rate of curing, but it also provides a greater maximal curing depth, which may be desirable in some 3D printers **100**. These two competing parameters of the photo-curing resin used for the print matrix **114** mean that there exists a tradeoff between curing rate and the maximum size for the cured object **180**.

[0031] The threshold for curing depends on the wavelength as opposed to the intensity of light. This is because the interaction between light and photoinitiators is quantum mechanical in nature. Light intensity only determines the rate of curing, but it has no bearing on whether the curing process is started. Assuming a sufficient density of photoinitiating molecules, the curing rate scales linearly with light intensity. Ideally, a resin would have a curing rate of zero below a certain intensity threshold. Such a resin would have a highly nonlinear curing rate as a function of intensity, ideally approaching a step function. Hence, it is desirable to have the 3D real image **170** be provided with curing light **166** of a wavelength suited to the particular photoinitiators of the photo-curing resin (e.g., within a predefined curing wavelength range) and also above a minimum curing intensity (with nearby portions of the matrix **170** being exposed to lower intensity light). In this way, the curing process will be initiated at the location of the 3D real image **170** at a relatively quick curing rate (e.g., several minutes or less) to limit or avoid curing of nearby portions of the matrix **114**.

[0032] In some preferred implementations of the 3D printer **100**, the specific gravities of the cured and uncured resin should be as close to each other as possible. This is to ensure that the position of the cured portion of the resin (i.e., the generated 3D object **180**) does not change with respect to position of the liquid resin during the curing process as this ensures or facilitates creation of a distortion-free cured object **180**. Further, the indices of refraction of the cured and uncured resin should be as close to each other as possible. Depending on the shape of the object, it is highly likely that light will need to transmit through cured portions of resin. If the cured resin has a different index, light will refract and cause the image to distort. Still further, the photo-curing resin undergoes a chemical reaction during the curing process. This chemical reaction should be as isothermal as possible so as not to induce temperature gradients inside the vat **110**. Such temperature gradients would cause the uncured resin to flow, which distorts the cured object. In reality, most photo-curing resins are exothermic to some degree, and this can place an upper limit on curing rate. Hence, there is likely an inherent tradeoff between the curing rate and print resolution due to temperature gradients inside the vat **110** of resin **114**.

[0033] A different approach to selectively curing a portion or volume of the liquid print matrix **114** to generate the 3D object **180** is to use dual-wavelength excitation. In this embodiment of the 3D printer, the photo-curing resin used would include phosphors that absorb at two wavelengths and

emit a third wavelength, the resin's curing wavelength. These phosphors would be mixed into the resin and emit the wavelength necessary for curing. Such phosphors exist and can be engineered for photo-curing applications. In this approach, two or more real images **170** can be projected **166** by an optical assembly **160** into the resin **114** using light **128**, **150** of different wavelength. These images **170** would need to be accurately superimposed to generate the 3D object **180**. In this implementation of the 3D printer **100**, only resin **114** exposed to both wavelengths will cure, which both enhances curing rate and the maximum possible size of the cured object. The other aforementioned resin properties still apply in this approach.

[0034] Referring again to FIG. **1**, the 3D printer **100** is shown to include one or more light sources **120** that are selectively operated or controlled by a controller **122** with control signals **124** (wired or wireless communications). The controller **122** may be a computer or computing device including a processor(s) that manages input/output (I/O) devices to allow user input (e.g., to initiate a print operation, to select a curing time, and so on). The processor of controller **122** may also manage one or more storage devices/memory that store executable instructions (e.g., a printing program) to generate the control signals **124**. The control signals **124** may include or define a curing or exposure time for the matrix **114**, and curing times for each of a plurality of potential photo-curing resins used to provide the liquid print matrix **114** may be stored in memory or data storage of the controller **122**.

[0035] The light source(s) **120** is chosen to output illuminating light **128** with a wavelength falling in a curing wavelength range for the photo-curing resin **114** in the print chamber **110**. Also, the illuminating light **128** provide by the light source(s) **120** is of an intensity that is greater than a predefined intensity needed to achieve a desired curing rate of the photo-curing resin **114** (e.g., great enough intensity to account for intensity losses through the 3D printer components to the 3D real image **170**). The light source(s) **120** preferably is adapted to illuminate the entire outer surface **142** of a 3D object **140** targeted (or a target 3D object) for copying with the 3D printer **100**, and, in this regard, two, three, or more bulbs or other components, positioned around or encircling the 3D object, may be included in light source **120** to direct the illuminating light **128** onto each and every side (except a bottom or base side in this example) of the 3D object **140**.

[0036] The 3D printer **100** is shown to include a support or alignment stand **130** upon Which the target or existing 3D object **140** is positioned. For example, the stand **130** may include a planar upper surface **131** with one or more alignment markings provided to indicate a print position for the 3D object **140** to ensure light **150** reflected from its outer surface (s) **142** is directed by the optical assembly or optics **160** as curing light **166** fully into the liquid print matrix **114** in the print vat **110** (e.g., wholly place the 3D real image **170** within the liquid print matrix **114** to print a 3D object matching that of the target 3D object **140**). One or more of the outer surfaces **142** of the 3D object **140** may be treated to provide equal or more equal reflection of the illuminating light **128** so that all the surfaces **142** are more equally represented in the object-reflected light **150** (e.g., to provide more equal illumination of all surfaces **142** of the object **140** and avoid some that may absorb more light **128**, which may result in poorer quality 3D object **180** as portions of the real image **170** may not be as bright (or as well defined)).

[0037] The target 3D object **140** is shown to include one or more overhanging (or cantilevered) features **144**, with wings and arms shown in FIG. **1**, and, significantly, these features **144** do not require the generated 3D object **180** to include support structures as a portion or volume of the liquid print matrix **114** associated with the 3D real image **170** is nearly instantaneously cured and because the uncured portions of the matrix **114** underneath and nearby the overhanging features of the 3D object **180** act to support these forming or in-process features (e.g., due to the like specific gravities of the cured and uncured portions of the photo-curing resin chosen to provide the liquid print matrix **114** as discussed above).

[0038] The 3D printer **100** further includes an optical assembly or optics **160** that includes components that are selected and arranged to receive the object-reflected light **150** from the surfaces **142** of the target 3D object, and, in response, to reflect or direct light (i.e., curing light) **166** into the liquid print matrix **180** so as to display or project a 3D real image **170**. As discussed above, the light **166** providing the **31**) real image **170** has a brightness or intensity that is greatest at its portions corresponding to the outer surfaces **142** of the target 3D object **140** and that is greater than some predefined minimum intensity to achieve a desired curing rate. Also, the light **166** providing the 3D real image **170** is at a wavelength within a curing wavelength range for the photo-curing resin of the liquid print matrix **114**.

[0039] The image **170** is a "real" image versus a "virtual" image. In optics, a real image is an image which is located in the plane of convergence for the light rays that originate from a given object. Examples of real images include the image seen on a cinema screen (the source being the projector), the image produced on a detector in the rear of a camera, and the image produced on an eyeball retina (the camera and eye focus light through an internal convex lens). A real image occurs where rays converge, whereas a virtual image occurs where rays only appear to converge. In other words, real images, such as 3D real image **170**, are formed by actual light rays and, thus, can be used to cure the photo-curing resin or photopolymer **114** in the print vat **110**. The optical assembly **160** may include concave mirrors and converging lenses when the object **140** is placed further away from the mirror/lens than the focal point, but this real image **170** may be inverted in the 3D printer or additional components or design steps may be taken to make the 3D real image not inverted if useful for obtaining a better quality 3D object (e.g., one with a missing side or surface in a base portion as shown in FIG. **1** rather than at an upper and likely exposed surface of the 3D object **180**). If a viewer sees a reflected/redirected image **170** from the side in which the light rays leave the lens or mirror of the optical assembly **160**, a real image is one on the same side of the lens or mirror as the viewer, whereas a virtual image is one on the opposite side of the lens or mirror.

[0040] FIG. **2** illustrates a 3D print method (or object generation method) **200** of the present description, which may be carried out by operation and/or use of the 3D printer **100** of FIG. **1**. The method **200** starts at **210** such as with the selection of a photo-curing resin for use in forming 3D objects by exposing a portion or volume of the photo-curing resin concurrently to light in the form of or defining a real image. Further, an optical assembly may be selected for creating real images of 3D objects in step **210** along with one or more light

sources for illuminating all or most of the outer surfaces of the 3D objects with light that is useful for curing the selected photo-curing resin.

[0041] At **220**, the method **200** continues with providing a volume of the photo-curing resin in a container. The volume of resin is chosen to provide enough material to form a chosen 3D object (e.g., the bigger the 3D object the more resin will be required and can be provided in step **220**). The container provided in step **220** includes at least one wall or portion of a wall that is transparent (or substantially transmissive) to light in the wavelength range required for curing the photo-curing resin. Typically, one or more sidewalls of the container will be formed of a glass or clear plastic, ceramic, or the like to provide the desired level of light transmission.

[0042] At step **230**, a 3D object is chosen for copying, and the 3D object is position at a predefined position and with a predefined alignment or orientation relative to the optical assembly of the 3D printer. In general, the 3D object printing location is one that allows light reflected from its surfaces to be received by the optical assembly at a desired level of intensity and then redirected with adequate focus into the photo-curing resin in the container.

[0043] At step **240**, the method **200** continues with illuminating outer surfaces of the 3D object with light having a wavelength(s) that is useful for initiating the curing process of the photo-curing resin in the 3D printer's container or print chamber. For example, the photo-curing resin may have a curing wavelength range of 350 nm to 500 nm, and the light provided in step **240** may fall within this range, e.g., be light from a blue light source, from a violet light source, from an ultraviolet (UV) source, a combination of such sources, or the like. The light sources chosen to perfoini the illuminating step **240** are selected to provide light of an adequate intensity, even considering losses in the system, to exceed a predefined minimum light intensity to achieve a desired curing rate. Further, the light sources are positioned relative to the 3D object's print location/position to direct light onto all surfaces that are to be copied or included in the printed/generated 3D object (e.g., all surfaces, all surfaces except a base or supporting surface upon which the 3D object stands or is supported, and the like).

[0044] At step **250**, the optical assembly is used to generate a real image or 3D real image of the 3D object illuminated in step **240** by receiving light reflected from the 3D object's surfaces and reflecting and/or redirecting the light. The generated 3D real image is displayed or projected within the photo-curing resin in the container via the transparent wall (or portion of a sidewall) of the container. Due to the wavelength of the light used to form the real image, the curing process is initiated, and this process generally occurs at the highest rate where the real image is the brightest (i.e., at the portions of the real image corresponding to the outer surfaces of the 3D object illuminated in step **240** with a properly designed optical assembly). At step **260**, the method **200** continues with a determination of whether or not a time falling within the curing time range for the photo-curing resin has elapsed (e.g., this may vary with the intensity of the light but may range from 0 to 5 minutes or the like). If not, the method **200** continues at **260**.

[0045] If the time has elapsed and the resin is fully cured by the real image light, the method **200** continues at **270** with halting the illumination of the 3D object with the light sources. Step **270** may also include removing the cured resin from the container, in other words, removing the generated or printed 3D object from the uncured photo-curing resin in the container. At step **280**, the method **200** may continue with replenishing the photo-curing resin in the container such as by providing a replacement volume for that used to form the 3D object, by removing all resin and providing a new volume of the same or a different photo-curing resin in the container, and so on. The method **200** may end then at step **290** or may continue at **230** with positioning a new 3D object in the 3D printer or leaving the same 3D object in the printer and producing another copy of this object.

[0046] FIG. **3** illustrates an implementation of a 3D printer **300** with an exemplary optical assembly **360** for proving a real image **370** to concurrently cure a volume or portion of a photo-curing resin to provide a "printed" 3D object **380**. The printer **300** includes components found in the printer **100** of FIG. **1**, and these components are provided with like reference numbers including a print chamber or vat **110** with transparent or light-transmissive sidewalls **112** and including a volume of photo-curing resin **114** in the print chamber or vat **110**.

[0047] In the 3D printer **300**, the optical assembly **360** is shown to include first and second curved (e.g., parabolic) reflectors or minors **362**, **364**. The 3D object **340** that is to be copied or printed with 3D printer **300** is placed at the focal point(s) of the first parabolic mirror **362**. The 3D printer light sources **320** are provided on an opposite or back side of the mirror **362**, and illuminating light **321** from the sources **320** is directed to one or more light passageways in the mirror **362** as shown with arrows **323** to illuminate or light the outer surfaces of the 3D object **340** (except for a base or bottom surface that may be facing away from the mirror **362**). As discussed above, the illuminating light **321** is of a wavelength useful for curing the resin **114** (e.g., a wavelength within a curing wavelength range for the resin **114**), and is also of an intensity or brightness to achieve a desired curing rate for the resin **114** (e.g., greater than a desired minimum intensity level to account for any losses in the optical assembly **360** and/or the vat **110** and resin **114** prior to forming the real image **370**).

[0048] Because the 3D object **340** is placed at the focus of the mirror **362**, its inner or reflective surface **363** receives the light **390** reflected from the outer surfaces of the object **340** and directs this light in parallel lines as shown at **392**. The optical assembly **360** further includes a second parabolic reflector or mirror **364** for receiving the light **392** reflected by the first parabolic minor **362**. The second parabolic mirror **364** is arranged relative to the print chamber **110** and first parabolic mirror **362** such that its focal point or focus is within the print chamber **110** such as in the center or at a desired depth within the volume of photo-curing resin **114**. This can be seen in FIG. **3** where the second reflected or redirected light **394** from the object **340** is focused or projected into the resin **114** in the print chamber **110** to form the real image **370**. The light **394** is provided for a time falling within a curing time range for the resin **114** (at the wavelength and intensity of the light **394**), and this causes a volume or portion of the photo-curing resin **114** to cure in the shape of or matching the outer surfaces of the 3D object **340** from which the light **390** was reflected as is shown with the "printed 3D object **380**. In this way, the optical assembly **360** is useful for creating in one step a 3D object **380** from an existing 3D object **340** (e.g., an outer shell or hollow bodied object based on the 3D object **340**).

[0049] The 3D printer **300** of FIG. **3** may be thought of as providing an instantaneous (or nearly so with curing in 30

seconds to about 5 minutes or more) copier of physical objects using dual curved mirrors in its optical assembly optics that are used to provide or project a 3D real image. In this embodiment, two large parabolic mirrors may be used for reflectors **362**, **364**. The object **340** to be copied is placed at the focus of the first minor **362**. This first curved mirror **362** has a substantially "surrounding view" of the object **340**. Parallel rays of light **392** leaving this parabolic minor **362** (reflected from surface **363**) are focused by a second parabolic minor **364** into the center of a vat/chamber **110** of a transparent photo-curing liquid **114** as shown with arrows **394**.

[0050] The liquid **114** hardens quickly when exposed to the light **394** that provides the real image **370**. In one prototype, the inventors used a photo-curing resin specially formulated to provide a hardened/cured material providing 3D object **380** (the cured portion or volume of liquid **114**) that has the same index of refraction as the non-hardened liquid **114**. In this way, light **394** passing through one part of the object **380** to harden/cure another part of the 3D object **380** (e.g., passing through a surface proximate to the mirror **364** to a surface more distal to the mirror **364**) is not affected (at least not to a degree significant to achieving similar curing effects in liquid **114**) by passing through the first part of the cured and/or curing material of the 3D object **380**.

[0051] In addition, the prototyped 3D printer **300** used a resin **114** with a specific gravity in the hardened/cured state that was the same or within a small range (e.g., within plus or minus 10 percent or the like) to the specific gravity of the resin or liquid **114** in the uncured or unhardened state. As a result of these matching or nearly matching specific gravities, the free floating printed object **380** stays in place in the container during the curing process and does not fall because of gravity, which allows objects **380** to be printed that include overhanging or cantilevered features or element without requiring printing of support structures or layers (as is the case with conventional 3D printers).

[0052] During the printing with the 3D printer **300**, the objet **340** is lit brightly by light **323**, from light source(s) **320**, having a wavelength at which the photo-curing resin **114** in the print chamber or vat **110** hardens (or for which curing processes are initiated), and the optical assembly **360** is configured to respond to the object illumination by producing a real image in the photo-curing resin or liquid **114**. The object **340** typically is an opaque object with or without treated surfaces to provide uniform or more uniform reflectivity when struck by light **323**, but a translucent object **340** can also be copied with 3D printer **300** such as through internal illumination (e.g., placing a light source(s) within the body of the 3D object **340**). The real image **370** or light associated with or creating/proving the real image **370** acts to cure the resin **114** into a replica **380** of the original object **340**.

[0053] In other embodiments of 3D printers, the optical assembly may include a single mirror element that is rotated about a 3D object to provide a circumferential scan of the 3D object's outer surfaces and the mirror element may be configured to focus or project a real image of all the scans into a print chamber and the photo-curing resin it contains. Particularly, a single, large, curved reflecting mirror may be provided in the optical assembly of the printer, and this mirror may be rotated about a central axis of the 3D object (or a platform or other element supporting the 3D object.

[0054] A light source is provided that provides a high-power strip or line of vertical light, with the light source being a laser (or lasers) in some useful implementations. The line or strip of illuminating light is reflected off one or more outer surfaces of the 3D object being printed or copied, and the rotating mirror acts to reflect the object-reflected light as it rotates about the circumference of the 3D object. The mirror is selected and/or configured to focus the reflected light into the photo-curing resin provided in the print chamber of the 3D printer, and the reflected light creates an aerial image of the slice or slit of the 3D object lit or illuminated by the vertical strip or line of light from the light source.

[0055] As the mirror and light source rotate around the 3D object, the focused strip or line of reflected light creates a cumulative real image in the form of a shell of the 3D object in the photo-curing resin in the print chamber or vat. This shell is a 3D copy of the outside surfaces or surface structure of the 3D object to be copied by the 3D printer. Alternatively, the object and vat (which may be placed above or below the 3D object in any of these embodiments) can be rotated in the 3D printer such as on a center stand in front of a fixed or stationary scanner, which includes the light source and the curved mirror.

[0056] In these embodiments of the 3D printer, the printing or curing of a portion or volume of photo-curing resin in a vat is nearly performed concurrently as in other embodiments especially when the mirror (or object and vat) are rotated at relatively high rotation rates. Since the application of light is not continuous, the curing rate may be somewhat slower with this embodiment of the 3D printer. However, this 3D printer design allows for the use of somewhat smaller optics (e.g., a smaller parabolic or curved mirror), and it will be useful for generating a copy of a 3D object in a time period that most would still consider to be "nearly instantaneous" such as a full curing time that is up to hundred times (or more) faster than previous techniques (especially since the 3D printer only prints the outside shell of the 3D object chosen for using in printing/copying).

[0057] FIG. **4** illustrates a 3D printer **400** that may be used to implement the circumferential scanning mirror concept discussed above to create real images useful for curing a photo-curing resin. As shown, the 3D printer **400** includes an optical assembly **420** with a rotation mechanism **410** such as a turntable or similar device with a mirror support **412**. The optical assembly **420** includes a curved mirror (e.g., a parabolic mirror) **422** that is mounted to the mirror support **412** so as to allow the rotation mechanism to rotate the mirror **422** with its reflective or mirrored surface **423** (which faces inward or toward a rotation axis **429**) about a rotation axis **429**.

[0058] A light source(s) **430** (e.g., one or more lasers or the like) may be mounted on a back surface of the curved mirror **422**, and a slit or elongated, linear light passageway (not shown) may be provided in the mirror **422** and its reflective surface **423** to allow the passage of a linear strip or line of illuminating light **432**. The 3D printer **400** further includes a support and/or alignment platform **440** (which may be hanging or otherwise supported above (or below) the rotation mechanism **410**) for receiving and supporting a 3D object **450** that has been selected for copying/printing by the 3D printer **400**. The rotation axis **429** of the rotation mechanism **410** and mirror **422** may run through this platform **440** and, when in place on the platform, through the target 3D object **450**. The platform **440**, in this example, is stationary when the 3D printer **400** is operated to print a 3D object **494**.

[0059] As shown during printing operations, the mechanism **410** functions to rotate, as shown with arrow **428**, the scanning mirror **422** about 360 degrees about the rotation axis **429** and about the circumference of the 3D object **450**. The light source **430** is concurrently operated to provide the vertical line or strip of illuminating light **432**. As a result, a thin strip or line **454** is illuminated on the outer surfaces **452** of the 3D object **450** at each position of the mirror **422** and light source **430** during this rotation **428**.

[0060] This causes a plurality of strips of light (object-reflected light) **458** to be reflected from the 3D object **450**, and the mirrored surface **423** of the mirror **422** receives this light **458** and directs/focuses it as shown with arrows **460** toward the print chamber or vat **110** to provide a plurality of strips or displayed real images **490** in the photo-curing resin **114**. These many real image or strips **490** when accumulated generate a whole real image **494** corresponding with the shell or outer surfaces **452** of the 3D object **452**, and, when the portion or volume of the photo-curing resin **114** associated with (or at the location of) the whole real image **494** cures or hardens, the printed 3D object **495** is formed or "printed." The curing or hardening may take numerous rotations **428** of the mirror **422** about its rotation axis **429** and projections of the real images **490** into the resin **114**.

[0061] In other embodiments of the 3D printers using photo-curing resin to provide nearly instantaneous printing of 3D objects, it may be desirable to utilize 3D real images that are created from digital files or other sources rather than from light reflected from existing 3D objects (e.g., real images not taken from a target 3D object as discussed with reference to FIGS. **1-4**). Tn one example of such a 3D printer, the optical assembly (and controller **122** and light source(s) **120** of the printer **100** of FIG. **1**) may take the form of a volumetric display device or system. There are a number of designs of volumetric display devices that may be utilized, with each generally acting to take a digital file defining a 3D object as input and displaying a 3D real image with volume in a display space. To practice the 3D printer, the position of the 3D real image or volumetric image would be chosen to be within the print chamber or vat or, more accurately, wholly within the liquid print matrix provided therein (e.g., at a depth within a volume of photo-curing liquid or resin). The light used to display the volumetric image is used to initiate curing to form the 3D object in a nearly instantaneous manner.

[0062] In one particular embodiment, one of the volumetric display devices taught in U.S. Patent Application Publication No. 2014/0028663 A1, which is incorporated herein in its entirety, are used to provide a volumetric image in a volume of photo-curing resin (or other liquid print matrix) so as to generate a 3D object from a digital image file (e.g., from an image of an object the may or may not exist in the physical world or without a need for copying of a physical object). FIG. **5** illustrates a 3D printer **500** incorporating one embodiment of volumetric display device **510** to provide a volumetric image using a vibrating mirror (or, more accurately, a van-focal beamsplitter) to rapidly and essentially simultaneously image the layers of a computer-generated object (or image file) inside a vat or print chamber containing a photo-curing polymer. In this way, existing objects defined by a digital file or even objects that never previously existed in the real world can be printed.

[0063] The 3D printer **500** may make use of the "vaiifocal" effect, which can be achieved with one or more inertial drivers that shake or vibrate the rim or frame supporting the beam-splitter, which is formed of a flexible sheet of reflective and transmissive material such as circular sheet of flexible aluminized polyester or Mylar® (such an arrangement is also called a scrim mirror). The image generator, which provides images to the backside of the beamsplitter, may be a transmissive display, such as an RGB liquid crystal (LC) panel, which is backlit by an addressable light source, such as an LED array, a high-speed video projector, or the like. In this manner, the volumetric display generates volumetric real images with addressable depth planes, such as at a block level with use of an LED array light source or at the pixel level with use of a high-speed video projector as the backlight for the transmissive display.

[0064] FIG. **5** illustrates with a schematic or functional block representation the 3D printer **500** with a volumetric display system. As shown, the 3D printer **500** includes a print chamber **110** as found in the system **100** of FIG. **1** which is filled with a liquid print matrix **114** such as a volume of photo-curing resin or liquid. All the other components of printer **500** shown in FIG. **5** are use to provide a volumetric image **560** in the liquid print matrix **114** to initiate its curing to form a printed 3D object **580**, and these other components may be considered the volumetric display system (or optical assembly, light source, and controller as labeled in printer **100** of FIG. **1**.

[0065] The volumetric display system of printer **500** includes a varifocal beamsplitter **510** arranged at an angle, θ, relative to horizontal such as an angle of 30 to 60 degrees (e.g., 45 degrees or the like), with such an angle being useful to present a volumetric image **560** along a targeting line to place the volumetric image **260** within the print chamber **110** and resin/liquid **114** (but other beamsplitter angles, θ, may be used for differing display axes to suit different applications).

[0066] The beamsplitter **510** is "varifocal" due to being shaken or vibrated such that it is planar (due to tensioning) when at rest or the 3D printer **500** not operating and then is cycled between a convex shape (outer or front side **514** curved outward a distance toward the print chamber **110**) and a concave shape (front side **514** curved inward a distance (e.g., the same distance) away from the print chamber/vat **110**). These movements may be considered "strokes" of the beamsplitter **510** and differing planes **564** of the volumetric image **560** are shown in the image space **567** (which coincides with the liquid print matrix **114** of chamber **110**) during such strokes (e.g., all on the forward stroke, all on the back stroke, or a combination thereof) to provide the depth of the image space **567**. The volumetric image is "real" because the space **567** is on the print chamber **110** side or out from the front side **514** of the beamsplitter **510** (rather than being a virtual image a distance behind the back side **518** of the beamsplitter **510**).

[0067] As shown in FIG. **5**, a set of source or input images **522** are provided by a screen of a transmissive display **520**. The transmissive display **520** may take the foiiii of an LC panel, and a controller **550** may provide black and white or full color images to the display **520** for use in generating image stream **522**. All or portions of the transmissive display **520** are backlit by a backlight or light source **526**. As discussed with reference to FIGS. **1-4**, the light source **226** may be chosen to provide light **222** having a wavelength suited to the particular photo-curing resin or liquid **114** in the chamber **110** so as to initiate curing processes where the volumetric image **260** is displayed (e.g., of a wavelength falling in a curing wavelength range of a photopolymer or the like). Also, the intensity of the light **222** from backlight **226** through the

display **220** may be chosen to be of a magnitude useful for achieving a desired cure rate (with higher intensities typically preferred to provide very rapid curing of the resin **114** to form a 3D object **580** in the vat **110**). The backlight **526** is typically addressable such that portions or even pixels may be selectively backlit on the display **520**, e.g., to form the print layers or real image display planes **265** that make up the volumetric image **260** in image space **267** and cause selective curing of the resin/liquid **114**.

[0068] The controller **550** may use a depth map to control operation of the backlight **536** while using a high-resolution color map to control the transmissive display **520**. These two maps may be synchronized, with each other and with vibration of the beamsplitter **510**, to control the content of the input or source images **522** (defining a 3D object **580** to be printed with printer **500**) and, consequently, the content of each real image display plane **565** in the volumetric image **560**, e.g., what image is visible in each spaced apart real image plan **565** and what light will be provided in the chamber **110** to cure the resinfliquid **114** to form object **580**. The spacing between planes **565** and the overall depth of the image space **567** is controlled by the deflection of the beamsplitter **510** and the timing of the backlight **526** in illuminating the transmissive display **520**.

[0069] The source image **522** from the screen/surface of display **520** is directed to the back side **518** of the varifocal beamsplitter **510**. A portion of this light (such as about 50 percent) is reflected as shown at **524** onto a reflective surface of a concave mirror **530** (which is fixed/rigid, unlike the beamsplitter/mirror element **510**), and the concave mirror **530** is chosen to have a focal point for the received light **524** within the liquid print matrix **114** contained in the print chamber or vat **110** so as to provide a real image rather than a virtual image (e.g., a focal point defining the image space **567** in combination with movement or the stroke of the beamsplitter **510**). The light **534** is reflected from the concave mirror **530** back toward the beamsplitter **510**, which allows a portion **538** (such as 50 percent) to pass through to the print chamber or vat **110**. This allows light associated with or used to provide the volumetric image **560** in the image space **567** to be used to initiate curing of the photo-curing liquid or resin **114** in the print chamber **110**. Since only about 25 percent of the light from source **526** reaches the print chamber, it is typically preferable to use a high illumination source such as 300 to 2000 lumens (with 1500 or more typically being preferred) to achieve higher curing rates to quickly (e.g., in 30 seconds to 5 to 10 minutes or more compared with hours taken by conventional 3D printers) form or print the 3D object **580**.

[0070] The image **560** is provided as a sequential number of real image display planes **565**, which substantially concurrently cure differing volumes or portions of the resin/liquid **114** to provide a more solid 3D object **580**. In some cases, a hollow shell can be provided by the planes **565** by displaying only outer layers of an object, but, in other cases, the interior space of the object **580** may be displayed to allow internal components of the object **580** to be printed, too. For example, a honeycomb in-fill may be provided by the layers/planes **565** or meshing/working components that are covered by an outer layer or shell may be provided by the image display planes **565**. The greater the number of planes **565**, the more "solid" the image **560** will appear and the more dense layers will be in the printed 3D object **580**. However, the printer **200** can be practiced with as few as 2 to 3 planes up to 10 or more planes depending on factors such as the speed with which the backlight can vary which portions of the display screen **520** are illuminated (address sets of pixels or the like to define the differing content provided in each plane **565**).

[0071] In one embodiment, the backlight **526** is an LED array configured such that each LED may be addressed and separately strobed such that one or more LEDs may be used by the controller **550** to backlight the transmissive display (e.g., an LC panel) **520**. The size of the LED array may vary to suit the size of the LC panel **520** such as a 16 by 16 array of LEDs arranged in an addressable matrix. Light **522** from this LC/LED combination (**520**/**526**) is reflected by the beamsplitter **510**, e.g., a half-silvered varifocal beamsplitter. A portion of the reflected light **524** is directed toward the fixed concave mirror **530**. The concave mirror **530** focuses light **534** back onto and through **538** the beamsplitter **510**, where it forms stacked real images **565** of the surface of the LC or transmissive display **520** in a space or location **567** within the liquid print matrix **114** of the print chamber **110** that is positioned in front of the varifocal beamsplitter **510** or its front side/surface **514**. In one implementation, the mirror **530** is a fixed concave, f/2, 0.75 meter, diagonal mirror. This concave mirror **530** can be used to reflect the light **524** back through it as shown with arrows **534** and **538**. This concave mirror **530** can be used to provide up to an approximately 0.3 meter diagonal real image **560** extending out into the viewer space (shown with image space **567** that is located past the front surface/side **514** of the beamsplitter **510** in the resin/liquid **114**). It should also be understood that the use of the concave mirror **530** also corrects a depth inversion issue inherent in some volumetric display systems.

[0072] In one exemplary implementation of the 3D printer, the primary image source or transmissive display **520** could be an off-the-shelf 15-inch diagonal LC panel with its backlight removed. The backlight **526** may be a custom-built 16 by 16 array of high brightness, white-light, diffused LEDs. This array **526** can then be used to illuminate the LC panel **520** at up to 320 depth planes per second. During each depth frame, selected LEDs were strobed for approximately 2 milliseconds to set depth plane positions (e.g., planes **565**) in a volume (e.g., image space **567** of volumetric image **560**). In one implementation, 8 depths (e.g., planes **565**) could be independently selected in **556** separate areas (16 times 16), which may lead to an egg crate-type artifact that can be eliminated, if desired, through the use of a backlight **526** in the form of a high-speed projector providing light of a desired resin-curing wavelength (e.g., to allow pixel-by-pixel mapping of light to display **520**).

[0073] To create the volumetric images **560**, the controller **550** can be adapted to provide synchronization of the image on the LC display **520**, the LED or other backlight **526**, and the beamsplitter drive used to resonate the flexible mirror element or varifocal beamsplitter **510**. In one prototype, such synchronization was achieved with a frame sync signal from which all other timing signals were derived. Particularly, a sine wave version of the frame sync was power amplified and used to drive the beamsplitter transducers/drives (which were connected in series). An adjustable delay line was used to adjust for a fixed phase delay due to the mirror/beamsplitter **510** dynamics. Backlight patterns for backlight **526**, associated with 3D objects **580** to be printed, can be stored by the controller **550** and downloaded by a serial link to a microprocessor, and a pulse version of the frame sync was used to load

the backlight frame data (e.g., used to control an LED array) from the microprocessor to the backlight (e.g., LED array) via a dedicated parallel data path.

[0074] The controllers described herein may be a desktop computer, a workstation, a laptop or pad computer, or other computer device operable by a user of the 3D printer to select and transmit a digital model to the display **520** for use in printing the 3D object **580**. To this end, the controller may include a processor or central processing unit (CPU) that operates or manages input and output (I/O) devices such as a monitor, a touchscreen, a mouse, a keyboard, speakers, voice recognition devices, and the like that allow an operator or user of the controller **550** to provide user input. Particularly, the controller **550** may include memory devices or data storage components (e.g., non transitory computer readable medium) (or have access to such memory devices) that are managed by the processor to store one or more digital files that are used to print a 3D object **580**. Also, the controller **550** may use the CPU to execute code or software (in computer readable medium such as RAM, ROM, or the like on the system **550**) in the form of a 3D printer interface program.

[0075] In practice, the 3D printer interface program may be adapted to cause a series of interface screens to be presented by the controller **550** and its I/O devices to a user. The user may select a 3D object for printing by first generating a 3D model of a 3D object made up of a number of object elements, and this definition may also include setting a thickness for an outer shell of object and a structural infill (e.g., one or more honeycomb patterns). Then, during operations, the controller **550** is operable to communicate (wirelessly or in a wired manner) with the transmissive display **520** and backlight/light source(s) **526** including transmitting a frames of a digital model to print a 3D object **580** by operating the volumetric display device of the 3D printer **500**.

[0076] Although the invention has been described and illustrated with a certain degree of particularity, it is understood that the present disclosure has been made only by way of example, and that numerous changes in the combination and arrangement of parts can be resorted to by those skilled in the art without departing from the spirit and scope of the invention, as hereinafter claimed.

[0077] For example, many of the examples provided herein perform imaging with curved mirrors, but the embodiments may be provided that refractive lenses or other focusing optics may also be used to create the real images used to "print" a 3D object with the 3D printers taught herein. In general, any optical system that is capable of creating a floating, aerial real image can be used in one of the 3D printers of this description.

[0078] The 3D printers provide a number of advantages over prior 3D printers. The 3D printers are inherently faster as they produce an object literally with a flash of curing light. The 3D printer are also more cost effective with regard to printing materials, especially in the case of a cylindrical or circumferential scan, since the 3D printers may be used to only create an outer shell of an object, which only uses the amount of photo-curing material required for this shell (and not an interior in-fill and, when needed, a support structure for cantilevered/overhanging elements) Some of the 3D printers are specially adapted for use in copying existing 3D objects while other 3D printers described herein can be used to create objects from images of 3D objects such as from outputs of 3D cameras or computer-generated images/models of objects.

[0079] There are many ways that the 3D "printing" may be achieved with a liquid print matrix (such as matrix **114** in FIG. **14**), but it may be useful at this point in the description to discuss properties of photocuring resin and a couple of useful approaches for forming a 3D printing using a real image as taught herein.

[0080] In a first approach, curing an object by forming a 3D real image in a vat of photo-curing resin is achieved utilizing particular resin properties. The resin may be selected so as to contain photoinitiators that absorb a certain wavelength of light, which initiates a crosslinking or polymerization process. This causes the polymer to physically harden. The resin can cure at either a visible or invisible wavelength. This depends on the wavelength absorbed by the photoinitiator. The inventors have cured (formed a 3D object) using blue light (450 nm), violet light (405 nm), and ultraviolet light (365 nm). Resins that cure with invisible wavelengths are less affected by ambient light.

[0081] In this first printing approach, the resin acts to both absorb and transmit light at the curing wavelength. Higher absorption results in a faster rate of curing but also a shorter maximal curing depth. The maximal curing depth determines the size of the largest object that can be cured. High transmission results in a slower rate of curing but also a longer maximal curing depth. These two competing requirements mean that there exists a tradeoff between curing rate and the maximum cured object size.

[0082] The threshold for curing depends on the wavelength as opposed to the intensity of light. This is because the interaction between light and photoinitiators is quantum mechanical in nature. Light intensity only determines the rate of curing but has no bearing whether the curing process is started. Assuming a sufficient density of photoinitiating molecules, the curing rate scales linearly with light intensity. Ideally (or at least preferably in many applications), a resin would have a curing rate of zero below a certain intensity threshold. Such a resin would have a highly nonlinear curing rate as a function of intensity, ideally approaching a step function. If such a resin cannot be identified, a resin with properties approaching or nearer these ideal properties may be used in its place.

[0083] The specific gravities of the cured and uncured resin may be chosen so as to be as close to each other as possible. This is to ensure that the position of the cured portion of the resin does not change with respect to position of the liquid resin during the curing process, which is desirable to ensure a distortion-free cured object (and the inventors have identified resins with such properties). Additionally, it may be useful for the indices of refraction of the cured and uncured resin to be as close to each other as possible. Depending on the shape of the object, it is highly likely that light will need to transmit through cured portions of resin. If the cured resin has a different index, light will refract and cause the image to distort. Again, the inventors have identified resins with closely matched indices in both cured and uncured states. Further, the photo-curing resin undergoes a chemical reaction during the curing process, This chemical reaction should, hence (at least in many applications), be as isothermal as possible so as not to induce temperature gradients inside the vat. Such temperature gradients would cause the uncured resin to flow, which distorts the cured object. In practice, many photo-curing resins are exothermic to some degree, and this places an upper

limit on curing rate. There is an inherent tradeoff between the curing rate and print resolution due to temperature gradients inside the vat of resin.

[0084] In another approach to 3D "printing," dual-wavelength excitation may be utilized to form a 3D object with a real image in a liquid print matrix (such as matrix **114** of FIG. **1**). This approach could use phosphors that absorb at two wavelengths and emit a third wavelength, the resin's curing wavelength. One or more of such phosphors would be mixed into the resin and emit the wavelength necessary for curing. Such phosphors exist (are readily available) and can be effectively engineered for the photo-curing applications/printing processes taught herein. In this approach, two or more real images can be projected into the resin using light of different wavelength. These images would typically be accurately superimposed. Only resin exposed to both wavelengths will cure, which both enhances curing rate and the maximum possible size of the cured object. The other aforementioned resin properties still apply in this approach.

We claim:

1. An apparatus for generating a physical three dimensional (3D) object, comprising:

a print chamber with one or more sidewalls enclosing an interior void adapted for containing liquids;

a liquid print matrix positioned in the interior void of the print chamber; and

an optical assembly operating to focus light into the interior void of the print chamber o initiate curing processes for a volume of the liquid print matrix to form a 3D object.

2. The apparatus of claim **1**, wherein the liquid print matrix comprises a volume of a photo-curing resin.

3. The apparatus of claim **2**, wherein the photo-curing resin comprises a photopolymer.

4. The apparatus of claim **2**, wherein the light focused into the print chamber has a wavelength within a wavelength curing range for the photo-curing resin.

5. The apparatus of **4**, wherein the photo-curing resin is transmissive of light having a wavelength in the wavelength curing range when in liquid form and when in hardened form.

6. The apparatus of claim **4**, wherein the photo-curing resin has a first specific gravity in a liquid form and a second specific gravity when cured and wherein the second specific gravity is in a range of 90 to 110 percent of the first specific gravity, whereby the formed 3D object is supported by adjacent uncured portions of the photo-curing resin in the print chamber.

7. The apparatus of claim **1**, wherein the light focused into the print chamber displays a real image defining at least an outer shell of the 3D object.

8. The apparatus of claim **7**, wherein the optical assembly comprises refractive lenses or other focusing optics generating the real image.

9. The apparatus of claim **7**, further comprising a light source illuminating outer surfaces of a target 3D object, and wherein the optical assembly comprises a first curved mirror receiving and reflecting light reflected from the outer surfaces of the target 3D object and wherein the optical assembly further comprises a second curved mirror receiving and reflecting the light reflected from the first curved mirror as the light focused into the print chamber.

10. The apparatus of claim **7**, wherein the optical assembly comprises curved mirror, a light source directing light through the curved mirror, and a rotation mechanism rotating the curved mirror and the light source along a circular path about a target 3D object, wherein the light source illuminates a plurality of vertical strips of outer surfaces of the target 3D object as the light source and the curved mirror are moved along the circular path, and wherein the curved mirror reflects light reflected from the outer surfaces of the target 3D object to provide the light focused into the print chamber.

11. The apparatus of claim **7**, wherein the real image comprises a volumetric image displayed by a volumetric display device.

12. The apparatus of claim **11**, wherein the volumetric image is defined a 3D digital model comprising frames used to sequentially display a plurality of real image display planes in an image space coinciding with the interior void of the print chamber.

13. A 3D printer, comprising:

a tank containing a volume of a photo-curing liquid;

a light source directing light, having a wavelength that initiates curing of the photo-curing liquid, onto a 3D object; and

optics receiving portions of the light reflected from surfaces of the 3D object and, in response, displaying a real image within the photo-curing liquid.

14. The 3D printer of claim **13**, wherein the optics include a first parabolic mirror positioned to focus upon the 3D object and further include a second parabolic mirror receiving the reflected light from the surfaces of the 3D object via reflection from the first parabolic mirror, wherein the second parabolic mirror is configured to focus within the tank to provide display the real image.

15. The 3D printer of claim **13**, wherein the optics comprise a curved mirror and light source rotating circumferentially about the 3D object and to direct a plurality of linear scan strips into the tank that in combination provide the real image.

16. The 3D printer of claim **13**, wherein the photo-curing liquid comprises a photopolymer with a first specific gravity when liquid and a second specific gravity when cured to a solid that is within 10 percent of the first specific gravity and wherein the photopolymer has a first transmissivity to light when liquid and a second transmissivity that is substantially equal to the first transmissivity to light when cured to a solid.

17. A method for forming a 3D object, comprising:

providing a volume of photo-curing resin;

displaying a real image of a target 3D object for printing within the photo-curing liquid, wherein light used to display the real image has a wavelength in a curing wavelength range for the photo-curing resin; and

continuing the displaying of the real image for a curing time for the photo-curing resin at an intensity of the light used to display the real image.

18. The method of claim **17**, wherein the curing time is less than 5 minutes.

19. The method of claim **17**, wherein the real image comprises a volumetric image generated from a digital image file defining a plurality of frames to be displayed on spaced apart real image display planes within the photo-curing resin.

20. The method of claim **17**, wherein the display of the real image comprises illuminating outer surfaces of the target 3D object with light of the wavelength in the curing wavelength range and focusing reflected portions of the light reflected from the illuminated outer surfaces into the photo-curing resin.

21. The method of claim **20**, wherein the illuminating of the outer surfaces comprises sequentially directing elongated

strips of the light of the wavelength in the curing wavelength range onto adjacent portions of the outer surfaces of the target 3D object and wherein the sequentially directing step is performed a plurality of times during the continuing of the displaying of the real image step, whereby the adjacent portions of the outer surfaces are illuminated the plurality of times.

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