

SYSTEM, METHOD, AND FRAME FOR FABRICATING AN ARTICLE

CROSS-REFERENCE TO RELATED APPLICATIONS

[001] This application claims the benefit of priority to U.S. Provisional Application No. 63/536,714, titled “SYSTEM, METHOD, AND FRAME FOR FABRICATING AN ARTICLE”, filed on September 06, 2023. The content of the above document is incorporated by reference in its entirety as if fully set forth herein.

FIELD OF THE INVENTION

[002] The present invention relates generally to systems and methods of fabricating articles. More specifically, the present invention relates to systems, methods and frames for fabricating an article, using fluidic shaping methods.

BACKGROUND OF THE INVENTION

[003] Many articles require highly polished surfaces which are hard and costly to achieve. Polished curved surfaces are even harder to achieve. For example, the fabrication of optical articles such as lenses and curved mirrors relies on mechanical processing such as grinding and machining, followed by polishing the optical surfaces. The requirement for high-quality surfaces requires specialized and expensive equipment, and the fabrication of non-standard optical surfaces remains a challenge.

[004] Limited access to corrective eyewear remains a significant medical, societal, and economic challenge, even in the 21st century. More than 1 billion people suffer from uncorrected vision impairment, with the vast majority residing in developing countries. Decades of philanthropic efforts failed to supply even a small fraction of the demand, whereas local manufacturing using standard machining technologies remains out of reach due to inadequate resources.

[005] Fabrication of tailored lenses at the point of sale (e.g., the optometrist shop) is impossible and impractical using the known mechanical methods.

[006] Accordingly, there is a need for a simple fabrication method, that can be implemented at the point of sale, or in rural areas, that will ensure high-quality surfaces for any desired topography.

SUMMARY OF THE INVENTION

[007] Some aspects of the invention may be directed to an article fabrication system, comprising: a chamber configured to hold an immersion liquid; a divider comprising a through opening, dividing the chamber into at least one first portion and at least one second portion, the divider comprising an article frame and a gasket located between the divider and the frame; an immersion liquid hydraulic system comprising at least one control valve and at least one bidirectional immersion liquid pump, wherein the immersion liquid hydraulic system is configured to: allow equalization of the pressure between the at least one first portion and the at least one second portion; and adjust volume or pressure of the immersion liquid in the at least one first portion; a curable liquid provision unit comprising curable liquid reservoir, configured to provide curable liquid to the article frame; and a controller configured to: control the immersion liquid hydraulic system to equalize the pressure between the first and second portions; control the immersion liquid hydraulic system to block a flow between the first and second portions; control the curable liquid provision unit to provide the curable liquid to the article frame; and control the immersion liquid hydraulic system to either increase or decrease the amount or pressure of the immersion liquid in the first portion.

[008] In some embodiments, the immersion liquid hydraulic system further comprises: the at least one control valve is a pressure control valve fluidically connected between the at least one first portion and the at least one second portion and configured to allow equalization of the pressure between the at least one first portion and the at least one second portion; and wherein the at least one bidirectional pump is in fluid connection with the first portion configured to control the volume or the pressure of the immersion liquid in the at least one first portion.

[009] In some embodiments, the immersion liquid hydraulic system comprises two bidirectional pumps in fluid connection with the first portion, wherein a first of the two bidirectional pumps is configured to provide a solvent solution and a second of the two bidirectional pumps is configured to provide at least one solute solution, and wherein the controller is configured to control the first and second bidirectional pumps to provide the solvent and the solute at a predetermined ratio to form the immersion liquid.

[0010] In some embodiments, the system further comprises a first mixer for mixing the solvent solution and the solute solution prior to the provision of the immersion liquid into

the first portion. In some embodiments, the system further comprises a second mixer for mixing the solvent solution and the solute solution inside the chamber.

[0011] In some embodiments, the solvent solution has a density smaller than the density of the curable liquid and wherein the solute solution has a density higher than the density of the curable liquid. In some embodiments, the bidirectional pressure control valve is in fluid connection with the first portion, the second portion, and the at least one bidirectional pump.

[0012] In some embodiments, the curable liquid provision unit further comprises: a port configured to provide curable liquid from the curable liquid reservoir to the article frame; and at least one curable liquid bidirectional pump in fluid connection with the port and the curable liquid reservoir.

[0013] In some embodiments, the divider further comprises a dividing plate having the through opening; and a frame holder sealingly securing the gasket and the frame to the dividing ring. In some embodiments, the system further comprises at least one imaging device configured to capture light transmitted through or reflected from the curable liquid. In some embodiments, the at least one imaging device is at least one of, a camera and a wavefront sensor. In some embodiments, the controller is configured to: receive an image from the at least one imaging device; and control at least one of, the curable liquid provision unit, the immersion liquid hydraulic system, and the at least one light source, based on the image.

[0014] In some embodiments, the system further comprises at least one light source configured to illuminate the article. In some embodiments, the at least one light source is located at at least one of: end of the first portion opposite to the article frame, or end of the second portion opposite to the article frame, on a wall of the first portion or a wall of the second portion, and outside the closed chamber wherein the closed chamber comprises at least one transparent window located between the light source and the article. In some embodiments, the controller is further configured to control the at least one light source to provide light to the curable liquid. In some embodiments, the light source comprises at least one of, an array of light-emitting-diodes (LEDs), gas-discharge lamps and incandescent light bulbs. In some embodiments, the system further comprises a diffuser configured to diffuse the light over the article.

[0015] In some embodiments, the system further comprises a pressure sensor in fluid connection with the at least one first portion, and wherein the controller is configured to

control the immersion liquid hydraulic system based also on pressure measurements received from the pressure sensor. In some embodiments, the curable liquid and said immersion liquid are immiscible. In some embodiments, the density ρ_{im} of the immersion liquid varies from the density of the curable liquid ρ by less than 15 %. In some embodiments, the article is a curved article. In some embodiments, the article is an optical article and the curable liquid is at least partially transparent. In some embodiments, the article is a mold for optical fabrication.

[0016] Some additional aspects of the invention may include kit for article fabrication. The kit may include the article fabrication system according to any one of the embodiments disclosed herein; the immersion liquid; and the curing liquid.

[0017] Some additional aspects of the invention are related to a method of fabricating an article, comprising: providing an immersion liquid to at least one first portion and at least one second portion of a chamber divided by a divider; opening a valve between the at least one first and at least one second portions; providing a curable liquid to an article frame included in the divider; closing the valve; adjusting a volume or pressure of the immersion liquid in the at least one first portion using a pump, to control a curvature of the article; and curing the curable liquid to form the article.

[0018] In some embodiments, the method further comprises receiving measurements of pressure of the immersion liquid in the at least one first portion, and wherein adjusting the volume or the pressure of the immersion liquid in the first portion is done based on the pressure measurements and required characteristics of the article.

[0019] In some embodiments, curing the curable liquid comprises adjusting the volume or the pressure of the immersion liquid in the at least one first portion during curing. In some embodiments, the adjusting comprises one of: passively releasing access immersion liquid if the pressure in the first portion exceeds a predetermined threshold, and actively operating the pump to adjust the volume or the pressure of the immersion liquid in the at least one first portion.

[0020] In some embodiments, the article is a curved article. In some embodiments, the article is an optical article and the curable liquid is at least partially transparent. In some embodiments, the article is a mold for optical fabrication.

[0021] Some additional aspects of the invention are directed to a frame for manufacturing an article, comprising: an enclosure having a wall with variable heights along the enclosure's

contour. In some embodiments, the enclosure's contour is determined based on a receiving device, receiving the article. In some embodiments, the article is a lens or a mirror, and the receiving device is selected from eyewear frame, microscopes, telescopes, binoculars, and laser cavities. In some embodiments, the frame is an integral part of the receiving device.

[0022] In some embodiments, the variability of the height is determined based on an intersection of the enclosure's contour with a surface having a desired topography of the article. In some embodiments, the desired topography of the surface satisfies the following fluidic shaping equation:

$$\frac{r^2 h_{rr} \left(1 + \frac{1}{r^2} h_\theta^2 \right) + (r h_r + h_{\theta\theta}) (1 + h_r^2) - 2 h_\theta h_r h_{r\theta} + \frac{2}{r} h_r h_\theta^2}{\left(1 + h_r^2 + \frac{1}{r^2} h_\theta^2 \right)^{3/2}} = \pm (Ah+B) r^2$$

wherein r is a normalized radius variable, h is a normalized surface height variable, subscripts denote spatial derivatives of h with respect to a radial direction or to an azimuthal direction, and A and B are free parameters.

[0023] In some embodiments, at least a portion of a surface of the frame creates a connector for connecting at least one of, the frame and the article, to the receiving device. In some embodiments, an inner surface of the frame comprises one or more connector forming elements, thereby forming at least one connector on a contour of the article for connecting the article to the receiving device. In some embodiments, the at least one connector forming elements are selected from, a recess and a protrusion and any combination thereof. In some embodiments, an outer surface of the frame comprises the connector for connecting the frame to the receiving device.

[0024] Some additional aspects of the invention are directed to a method of making a frame for manufacturing an article, comprising: receiving a contour in a receiving device; determining an enclosure contour of the frame to fit the contour in the receiving device; receiving a desired topography of the article; determining heights of a wall of the enclosure, along the contour based on an intersection of the enclosure's contour with a surface having the desired topography; and fabricating the enclosure wall.

[0025] In some embodiments, the method further comprises adding at least one external connecting element to an outer surface of the frame, wherein at least one external connecting

element is configured to form a connector for connecting at least one of the frames and the article to the contour of the space in the receiving device.

[0026] In some embodiments, the desired topography of the surface satisfies the following fluidic shaping equation.

$$\frac{r^2 h_{rr} \left(1 + \frac{1}{r^2} h_\theta^2 \right) + (r h_r + h_{\theta\theta}) (1 + h_r^2) - 2 h_\theta h_r h_{r\theta} + \frac{2}{r} h_r h_\theta^2}{\left(1 + h_r^2 + \frac{1}{r^2} h_\theta^2 \right)^{3/2}} = \pm (Ah+B) r^2$$

wherein r is a normalized radius variable, h is a normalized surface height variable, subscripts denote spatial derivatives of h with respect to a radial direction or to an azimuthal direction, and A and B are free parameters.

BRIEF DESCRIPTION OF THE DRAWINGS

[0027] The subject matter regarded as the invention is particularly pointed out and distinctly claimed in the concluding portion of the specification. The invention, however, both as to organization and method of operation, together with objects, features, and advantages thereof, may best be understood by reference to the following detailed description when read with the accompanying drawings in which:

[0028] Figs. 1A, 1B, and 1C are illustrations of article fabrication systems, and a block diagram of the controllable components of the article fabrication system according to some embodiments of the invention;

[0029] Figs. 2A, 2B, and 2C are illustrations and a flowchart of steps in a method of fabricating an article according to some embodiments;

[0030] Fig. 3 includes illustrations of a model of a frame, and the frame for fabricating an article according to some embodiments;

[0031] Fig. 4 shows simulations of two frames and the result of curved lenses fabricated using these frames according to some embodiments;

[0032] Fig. 5 shows illustrations of additional two frames and the corresponding lenses fabricated using these frames according to some embodiments;

[0033] Fig. 6 is a flowchart of a method of manufacturing a frame according to some embodiments;

[0034] Figs. 7A, 7B, 7C, and 7D are an illustration of a lens and analytical results of the optical powers of the lens as a function of the frame geometry and the injected volumes according to some embodiments;

[0035] Fig. 7E is a flowchart for calculating a frame geometry and liquid volumes for fabricating a desired lens according to some embodiments; and

[0036] Figs. 8A, 8B, 8C, and 8D are experimental results and characterization of eyewear lenses fabricated using the fluidic shaping method according to some embodiments.

[0037] It will be appreciated that for simplicity and clarity of illustration, elements shown in the figures have not necessarily been drawn to scale. For example, the dimensions of some of the elements may be exaggerated relative to other elements for clarity. Further, where considered appropriate, reference numerals may be repeated among the figures to indicate corresponding or analogous elements.

DETAILED DESCRIPTION OF THE PRESENT INVENTION

[0038] One skilled in the art will realize the invention may be embodied in other specific forms without departing from the spirit or essential characteristics thereof. The foregoing embodiments are therefore to be considered in all respects illustrative rather than limiting of the invention described herein. Scope of the invention is thus indicated by the appended claims, rather than by the foregoing description, and all changes that come within the meaning and range of equivalency of the claims are therefore intended to be embraced therein.

[0039] Articles having curved surfaces are always harder to fabricate and those that also require high-quality curved surfaces (e.g., optical grade quality) are much harder. One promising technique for fabricating such articles is the use of fluidic shaping methods. In such a method, a curable liquid is injected into a frame immersed in an immersion liquid. The curable liquid fills the space between the walls of the frame forming the article. When cured (inside the immersion liquid) the curable liquid solidified, while maintaining the nature of the liquid/liquid interface, therefore, obtaining a very high-quality surface (e.g., optical quality).

[0040] A system, method, and frame according to embodiments of the invention may allow an accurate control of the curvature of the article, from both sides. In a nonlimiting example, the system, method, and frame may allow fabricating an optical lens at the optometrist shop based on a specific optometric prescription provided by the optometrist in real time. In some

embodiments, a first unit (e.g., a 3D printer, a small CNC machine, and the like) may fabricate the frame according, for example, to the optometric prescription. The fabricated frame may be then inserted into an article fabrication system according to some embodiments of the invention. In a nonlimiting example, the article may be an optical lens. [0041] In some embodiments, at least one surface of the article (e.g. lens) has a desired topography, characterized by Equation 1:

$$\frac{r^2 h_{rr} \left(1 + \frac{1}{r^2} h_\theta^2\right) + (r h_r + h_{\theta\theta}) (1 + h_r^2) - 2 h_\theta h_r h_{r\theta} + \frac{2}{r} h_r h_\theta^2}{\left(1 + h_r^2 + \frac{1}{r^2} h_\theta^2\right)^{3/2}} = \pm (Ah + B) r^2 \quad (1)$$

wherein r represents a normalized radius variable, h represents a normalized surface height variable, subscripts denote spatial derivatives of h with respect to the radial or azimuthal directions, and A and B are free parameters. In some embodiments, at least one optical surface of the lens is characterized by Equation 1. In some embodiments, each point on the at least one surface is characterized by Equation 1, wherein A and B are surface specific constants.

[0042] As used herein, the term “surface height” is defined as the vertical distance between the highest point and the lowest point on the surface of the article. As used herein, the term “radius” is defined as the horizontal distance between the highest point and the lowest point on the surface of the article. In some embodiments, the surface is the optical surface of the lens.

[0043] In a non-limiting example, there is the curable liquid of density ρ_{lens} injected into a cylindrical frame of radius R_0 and height d , suspended in an immersion liquid of density ρ_{im} . Another nonlimiting example for an elliptical frame is given with respect to Figs. 7A-7D, in the Examples section, herein below. It may be assumed that the lens liquid wets the inner walls of the cylinder and forms two separate interfaces with the immersion liquid, namely, an upper surface $u(r, \theta)$ (also refers as $h_{top}(x, y)$) and a lower surface $l(r, \theta)$ (also refers as $h_{bot}(x, y)$) (see Fig. 3 and Fig. 7A). The shape of these surfaces is determined by the balance of surface tension and gravitational forces, which can be characterized by the Bond number $Bo = \frac{R_0^2}{\ell_c^2} = \frac{|\rho|gR_0^2}{\gamma}$, where $\ell_c = \sqrt{\frac{\gamma}{|\rho|g}}$ is the capillary length, $\rho = \rho_{lens} - \rho_{im}$ is the density difference, γ is the interfacial energy between the two liquids, and g is earth gravity directed in the negative $\hat{z}$ direction. For $Bo \ll 1$, surface forces dominate over gravity, and

both surfaces take the shape of a spherical caps. For $Bo \gg 1$, gravity dominates over surface forces, rendering the configuration unstable and precluding the emergence of steady-state solutions. A parameter domain for which $Bo \approx 1$, i.e., when gravitational forces and surface forces are of comparable importance should be considered.

[0044] The upper and lower surfaces can be described by minimizing the free energy functional given by Equation 2.

$$\Pi = \gamma \int_0^{2\pi} \int_0^{R_0} F(r, \theta) dr d\theta \quad (2)$$

under the constraint of constant volume of the lens liquid, where $F(r, \theta)$ is given by Equation 3,

$$F(r, \theta) = \left(\sqrt{1 + \left(\frac{du}{dr}\right)^2} + \frac{1}{r^2} \left(\frac{du}{d\theta}\right)^2 + \sqrt{1 + \left(\frac{dl}{dr}\right)^2} + \frac{1}{r^2} \left(\frac{dl}{d\theta}\right)^2 + \frac{\rho g}{2\gamma} (u^2 - l^2) + \frac{\lambda}{\gamma} (u - l) \right) r \quad (3).$$

[0045] The first three terms under the integral sign represent the surface energy and the gravitational potential energy, respectively, while the last term represents the volume constraint, with a Lagrange multiplier λ .

[0046] An equilibrium is attained when the first variation of energy potential vanishes, i.e., $\delta\Pi = 0$, which yields the standard Euler-Lagrange equations, given in Equation 4

$$\begin{cases} \frac{\partial F}{\partial u} - \frac{d}{dr} \frac{\partial F}{\partial u_r} - \frac{d}{d\theta} \frac{\partial F}{\partial u_\theta} = 0 \\ \frac{\partial F}{\partial l} - \frac{d}{dr} \frac{\partial F}{\partial l_r} - \frac{d}{d\theta} \frac{\partial F}{\partial l_\theta} = 0 \end{cases} \quad (4)$$

which can be written explicitly as Equation 5

$$\begin{cases} \left(\frac{\rho g}{\gamma} u + \frac{\lambda}{\gamma} \right) r^2 - \frac{r^2 u_{rr} \left(1 + \frac{1}{r^2} u_\theta^2 \right) + (ru_r + u_{\theta\theta}) (1 + u_r^2) - 2u_\theta u_r u_{r\theta} + \frac{2}{r} u_r u_\theta^2}{\left(1 + u_r^2 + \frac{1}{r^2} u_\theta^2 \right)^{3/2}} = 0 \\ \left(-\frac{\rho g}{\gamma} l + \frac{\lambda}{\gamma} \right) r^2 - \frac{r^2 l_{rr} \left(1 + \frac{1}{r^2} l_\theta^2 \right) + (rl_r + l_{\theta\theta}) (1 + l_r^2) - 2l_\theta l_r l_{r\theta} + \frac{2}{r} l_r l_\theta^2}{\left(1 + l_r^2 + \frac{1}{r^2} l_\theta^2 \right)^{3/2}} = 0 \end{cases} \quad (5)$$

[0047] Following normalized variables are defined as follows by Equation 6.

$$R = r/R_0, \theta = \theta, U(R, \theta) = u(R, \theta)/h_0, L(R, \theta) = l(R, \theta)/h_0, P_0 = \frac{\lambda h_0}{\gamma \varepsilon^2} \quad (6)$$

wherein h_0 is the characteristic deformation length scale and $\varepsilon = \left(\frac{h_0}{R_0}\right)^2 \ll 1$. Upon substituting the variables in Equation 1.4 by normalized variables, Equation 7 is obtained:

$$\frac{R^2 U_{RR} \left(1 + \frac{\varepsilon}{R^2} U_\theta^2\right) + (R U_R + U_\theta \Theta) (1 + \varepsilon U_R^2) - 2 \varepsilon U_\theta U_R U_{R\theta} + \frac{2}{r} h_r h_\theta^2}{R^2 \left(1 + \varepsilon U_R^2 + \frac{\varepsilon}{R^2} U_\theta^2\right)^{3/2}} + Bo U = P_0 \quad (7)$$

[0048] Equation 7 and Equation 1 are equivalent. For given (e.g., measured) surfaces U, L and a fixed value of the dimensionless number Bo , P_0 is determined by Equation 1.6. For surfaces created by means of the method of the invention, there exists a value of Bo such that P_0 remains constant while R and Θ are varied through their domain of definition. If, on the other hand, the surfaces have been created via a different method, varying R and Θ will change the value of P_0 regardless of the value of Bo . A reasonable range for the value of Bo is between 0 and 100.

[0049] In some embodiments, the article has a non-spherical surface defined by Equation 1 or by Equation 7 is represented by Fig. 3.

[0050] In a nonlimiting example, the lens has an optical axis and a predetermined focal length.

[0051] Reference is now made to Fig. 1A and Fig. 1B which are illustrations of article fabrication systems according to some embodiments of the invention and to Fig. 1B which is a block diagram of controllable components of the article fabrication system according to some embodiments of the invention.

[0052] An article fabrication system 100 may include a chamber 110 configured to hold an immersion liquid and a divider 120, dividing chamber 110 into at least one first portion 112 and at least one second portion 114. In some embodiments, divider 120 may include an article frame 122 connected to an opening in divider 120. In the nonlimiting example illustrated in Fig. 1A, divider 120 may include a dividing plate 124 having the opening and a frame holder 126 securing and sealing frame 122 to dividing plate 124, for example, using gasket 128. In some embodiments, divider 120 may include only dividing plate 124 and frame 122, and frame 122 may be directly attached (e.g., glued) to dividing plate 124, using

a gasket made from sealing adhesive (e.g., a silicone-based adhesive), a metallic gasket, a composite material gasket and the like. Further disclosure regarding frame 122 is given with respect to Figs. 3, 4, 5 and 6 herein below.

[0053] In some embodiments, the immersion liquid is sufficient for immersion of at least one surface of the curable liquid. In some embodiments, the volume of the immersion liquid is sufficient for providing a buoyancy force to the curable liquid. In some embodiments, the volume of the immersion liquid is sufficient for contacting the surfaces of the curable liquid. In some embodiments, the density of the immersion liquid is determined according to a desired topography.

[0054] In some embodiments, the immersion liquid of the invention is characterized by sufficient rheological properties, such as viscosity, suitable for use thereof as an immersion liquid. One skilled artisan will appreciate, that an immersion liquid has to enable the formation of the desired topography, and/or geometric shape of the curable liquid volume immersed therewithin. In some embodiments, the immersion liquid of the invention is characterized by sufficient density so as to enable immersion of the curable liquid volume into the immersion liquid. In some embodiments, the density of the immersion liquid is set to provide a predetermined buoyancy (e.g. buoyancy sufficient for predefining a curvature of at least one surface of the curable liquid). In some embodiments, the density of the immersion liquid of the invention is set to provide neutral buoyancy conditions. In some embodiments, the density of the immersion liquid is set to provide conditions being within 30%, within 25%, within 20%, within 15%, within 10%, within 5%, within 3% deviation from the neutral buoyancy, including any range between. In some embodiments, the immersion liquid of the invention is immiscible with the curable liquid. In some embodiments, the immersion liquid comprises a hydrophilic liquid and the curable liquid is hydrophobic. In some embodiments, the immersion liquid of the invention comprises a lipophilic liquid and the curable liquid is hydrophilic. In some embodiments, the immersion liquid comprises a polar solvent (e.g., ionic aqueous solution). In some embodiments, the immersion liquid of the invention comprises water.

[0055] In some embodiments, the immersion liquid of the invention has a density different from the density of the curable liquid of the invention. In some embodiments, the density of the immersion liquid is greater than the density of the curable liquid. In some embodiments, the density of the immersion liquid of the invention is less than the density of the curable

liquid of the invention. In some embodiments, the immersion liquid of the invention has a density set to provide a buoyancy sufficient for predefining a curvature of at least one surface (e.g. upper surface) of the curable liquid. In some embodiments, the immersion liquid of the invention has a density set to provide a buoyancy sufficient for predefining a curvature of two surfaces (upper and lower surface) of the curable liquid of the invention. In some embodiments, the immersion liquid has a density set to provide a buoyancy sufficient for predefining a curvature of two surfaces (upper and lower surface) of the curable liquid of the invention.

[0056] In some embodiments, the immersion liquid of the invention comprises an aqueous solution. In some embodiments, the immersion liquid of the invention comprises an aqueous solution of a glycol. In some embodiments, the immersion liquid of the invention comprises an aqueous solution of a polyol. In some embodiments, the immersion liquid of the invention comprises glycerol or a mixture of glycerol and water. In some embodiments, the immersion liquid comprises water as a solvent and an additive, such as an organic and/or an inorganic salt (e.g. acetate, carbonate, halide, hydroxide, sulfate, thiosulfate, or bicarbonate salt), an organic water miscible compound (such as glycerin, methanol, ethanol, acetone). In some embodiments, the immersion liquid is chemically stable under curing conditions. In some embodiments, the immersion liquid has a boiling point compatible with the manufacturing conditions. In some embodiments, the immersion liquid is chemically inert with respect to the curable liquid. In some embodiments, the immersion liquid comprises a fluorocarbon oil. Such fluorocarbon oils are immiscible with most other liquids, and can thus serve as an immersion liquid for a variety of curable liquids. The density of the fluorocarbon oils can be controlled by mixing several types of fluorocarbon oils, or by mixing with specific organic compounds that are miscible therewith (e.g. Hexane). Such fluorocarbon oils comprise inter alia perfluoroperhydrophenanthrene, tetradecafluorohexane, methoxyperfluorobutane, 1H,1H,2H,2H-Perfluoro-1-octanol, Kritox, Fluorinert, Cytop, etc.

[0057] Article fabrication system 100 may further include an immersion liquid hydraulic system 130 comprising at least one control valve 132 and at least one bidirectional immersion liquid pump 134. System 130 is further illustrated in the block diagram of Fig. 1B. In some embodiments, immersion liquid hydraulic system 130 is configured to: allow equalization of the pressure between at least one first portion 12 and at least one second portion 14; and adjust volume or pressure of the immersion liquid in at least one first portion

12. In some embodiments, at least one control valve 132 may be a unidirectional valve, or a bidirectional valve. In some embodiments, pump 134 may be selected from, a plunger pump (e.g., a syringe pump), a positive displacement pump, a gear pump, roots-type pump, peristaltic pump, and the like.

[0058] In the nonlimited example illustrated in Fig. 1A, immersion liquid hydraulic system 130 may include a pressure control valve 132 fluidically connected between at least one first portion 12 and the at least one second portion and configured to allow equalization of the pressure between at least one first portion 112 and at least one second portion 114. In some embodiments, pressure control valve 132 may be a bidirectional valve. In some embodiments, immersion liquid hydraulic system 130 may further include at least one bidirectional pump 132 in fluid connection with first portion 112 and configured to control the volume or the pressure of the immersion liquid in at least one first portion 112.

[0059] In some embodiments, immersion liquid hydraulic system 130 may comprise two bidirectional pumps (not illustrated) in fluid connection with first portion 112, wherein a first bidirectional pump is configured to provide a solvent (e.g., water) solution and a second bidirectional pump is configured to provide at least one solute solution (e.g., ionic solution comprising salts). In some embodiments, the properties of the immersion liquid (e.g., density) is determined based on the ratio between the solvent solution and the solute solution.

[0060] In some embodiments, the solvent solution has a density smaller than the density of the curable liquid and wherein the solute solution has a density higher than the density of the curable liquid.

[0061] In such an embodiment, immersion liquid hydraulic system 130 may further include a first mixer for mixing the solvent solution and the solute solution prior to the provision of the immersion liquid into the first portion. In some embodiments, a second mixer may be placed inside first portion 112 and/or second portion 114 for ensuring homogeneous mixing of the solvent and solute.

[0062] In another nonlimiting example (not illustrated) immersion liquid hydraulic system 130 may include a bidirectional pressure control valve 132 and at least one bidirectional pump 134. Bidirectional pressure control valve 132 is in fluid connection with first portion 112, second portion 114, and at least one bidirectional pump 132. Bi-directional pressure control valve 132 may be configured to allow a flow between first portion 112 and second portion 114, while closing the flow to pump 134, and allow the flow from bidirectional pump

132 to first portion 112 while closing the flow between first portion 112 and second portion 114.

[0063] In some embodiments, immersion liquid hydraulic system 130 may include a pressure sensor 136 in fluid connection with at least one first portion 112 and configured to measure the pressure in first portion 112. In some embodiments, immersion liquid hydraulic system 130 may include an additional valve 138 configured to control the pressure of immersion liquid in first portion 112.

[0064] Article fabrication system 100 may further include a curable liquid provision unit 140, illustrated in Fig. 1C and 2A) configured to provide curable liquid to article frame 122. In some embodiments, curable liquid provision unit 140 may include a port 142 configured to provide curable liquid from a curable liquid reservoir 146 to article frame 122. In some embodiments, curable liquid provision unit 140 may further include at least one curable liquid pump 144 in fluid connection with port 142 and curable liquid reservoir 146.

[0065] In some embodiments, port 142 is configured for injecting of the curable liquid. Port 142 may be configured for injecting of the curable liquid, so as to obtain a predetermined volume of the curable liquid in contact with or in close proximity to frame 122. For example, port 144 may be configured for transferring the curable liquid on top, in close proximity, or in contact with frame 122.

[0066] In some embodiments, pump 144 may be controlled to provide a predetermined amount of curable liquid to port 142. In some embodiments, the amount is determined based on geometrical dimensions (e.g., the required size, curvature, desired topography, etc.) of the article (e.g., article 200 illustrated in Figs. 2A, 2C and 5). In some embodiments, pump 144 may be selected from, a plunger pump (e.g., a syringe pump), a positive displacement pump, a gear pump, a roots-type pump, a peristaltic pump, and the like.

[0067] In some embodiments, the term “curable liquid” refers to one or more fluid(s) capable of undergoing hardening or solidification. In some embodiments, the terms “curable liquid” and “hardenable liquid” are used herein interchangeably. In some embodiments, the curable liquid is capable to undergo solidification, so as to result in a solid or a semi-solid. In some embodiments, the curable liquid is in a solid state upon hardening or solidification. In some embodiments, the curable liquid is capable to undergo solidification, so as to substantially reduce its flowability. In some embodiments, the curable liquid is or comprises a liquid. In some embodiments, the curable liquid comprises a liquid capable of undergo

curing. In some embodiments, the curable liquid is in a liquid state. In some embodiments, the curable liquid comprises a liquid polymer. In some embodiments, the liquid polymer is curable. In some embodiments, the curable liquid comprises a curable polymer.

[0068] In some embodiments, the curable liquid is immiscible with the immersion liquid. In some embodiments, the immersion liquid comprises a hydrophilic liquid and the curable liquid is hydrophobic. In some embodiments, the immersion liquid of the invention comprises a lipophilic liquid and the curable liquid is hydrophilic. In some embodiments, the density ρ_m of the immersion liquid varies from the density of the curable liquid ρ by less than 15 %.

[0069] In a nonlimiting example, a curable liquid of the invention may refer to a composition comprising at least one of: a monomer, an oligomer, a polymer or a mixture thereof, wherein the composition is at least partially polymerizable (e.g. via free-radical polymerization) upon exposure to light in the UV and/or visible range. In some embodiments, the curable liquid is a liquid polymer comprising any methacrylate or acrylate resin which polymerizes upon exposure to UV light. In some embodiments, the polymerization occurs in the presence of a free radical photoinitiator. In some embodiments, the liquid polymer comprises one or more low molecular weight materials, such as methacrylates, dimethacrylates, triacrylates, and diacrylates, or any combination thereof.

[0070] In some embodiments, the curable liquid may include a photoinitiator, for example, an alpha-cleavage type (unimolecular decomposition process) photoinitiator or a hydrogen abstraction photosensitizer-tertiary amine synergist, operable to absorb UV light, preferably between 200 nm and 400 nm or between 300 nm and 385 nm, to yield free radical(s).

[0071] In some embodiments, the liquid polymer comprises a photopolymer. Some non-limiting examples of photo-polymerizable molecules comprise: styrene, N-Vinylpyrrolidone, allyl acrylate, diacrylates (such as epoxides, urethanes, ethers, or esters functionalized by acrylate), tetrahydrofurfuryl methacrylate, triethylene glycol dimethacrylate, 2-phenoxyethyl methacrylate, lauryl methacrylate, ethoxylated trimethylolpropane triacrylate, tricyclodecane dimethanol diacrylate, 2-phenoxyethylacrylate, triethylene glycol diacrylate, a monofunctional aliphatic urethane acrylate, polypropylene glycol monomethacrylate, polyethylene glycol monomethacrylate, cyclohexane dimethanol diacrylate, tridecyl methacrylate, tri(meth)acrylates (e.g., 1,1-trimethylolpropane triacrylate or methacrylate, ethoxylated or propoxylated 1,1,1-

trimethylolpropanetriacrylate or methacrylate, ethoxylated or propoxylated glycerol triacrylate, pentaerythritol monohydroxy triacrylate or methacrylate, hydroxyethyl methacrylate (HEMA), and tris(2-hydroxy ethyl) isocyanurate triacrylate) or any combination thereof.

[0072] Article fabrication system 100 may further include a controller 150 configured to control components of system 100, for example, immersion liquid hydraulic system 130 and curable liquid provision unit 140.

[0073] Controller 150 may include a processor 152 that may be, for example, a central processing unit (CPU) processor, a chip or any suitable computing or computational device. Processor 152 (or one or more processors, possibly across multiple units or devices) may be configured to carry out methods described herein, and/or to execute or act as the various modules, units, etc. More than one computing controller 152 may be included system 100 according to embodiments of the invention.

[0074] Controller 150 may include a memory 154 that may be or may include, for example, a Random Access Memory (RAM), a read only memory (ROM), a Dynamic RAM (DRAM), a Synchronous DRAM (SD-RAM), a double data rate (DDR) memory chip, a Flash memory, a volatile memory, a non-volatile memory, a cache memory, a buffer, a short term memory unit, a long term memory unit, or other suitable memory units or storage units. Memory 154 may be or may include a plurality of possibly different memory units. Memory 154 may be a computer or processor non-transitory readable medium, or a computer non-transitory storage medium, e.g., a RAM. In one embodiment, a non-transitory storage medium such as memory 154, a hard disk drive, another storage device, etc. may store instructions or code which when executed by a processor may cause the processor to carry out methods as described herein.

[0075] Memory 154 may be stored thereon, at least one of, an operating system, an executable code, and a database according to some embodiments of the invention.

[0076] Controller 150 may further include a communication unit 156 that may include one or more input and output devices. For example, the input devices may be or may include any suitable input devices, components or systems, e.g., a detachable keyboard or keypad, a mouse and the like. In another example, the output devices may include one or more (possibly detachable) displays or monitors, speakers and/or any other suitable output devices. Any applicable input/output (I/O) devices may be connected to controller 150. For

example, a wired or wireless network interface card (NIC), a universal serial bus (USB) device or external hard drive may be included in the input devices and/or the output devices.

[0077] In some embodiments, controller 150 may be configured to control immersion liquid hydraulic system 130 to equalize the pressure between first and second portions 112 and 114; control immersion liquid hydraulic system 130 to block a flow between first and second portions 112 and 114; control curable liquid provision unit 140 to provide the curable liquid to article frame 122; and control immersion liquid hydraulic system 130 to either increase or decrease the amount or pressure of the immersion liquid in first portion 112.

[0078] In some embodiments, controller 150 may be configured to receive pressure measurements from pressure sensor 136 and to control at least pump 134 and/or valve 138 based on the received measurements.

[0079] Methods according to embodiments of the invention to be executed by controller 150 are discussed in details with respect to the flowchart of Fig. 2B.

[0080] In some embodiments, system 100 may further include at least one light source 160 configured to illuminate the article. In some embodiments, at least one light source 160 is located at at least one of: end of first portion 112 or second portion 114 opposite to the article frame 122 (as illustrated), a side article frame 122, on a wall of first or second portions 112 and 114, and outside chamber 110. In such a case chamber 110 comprises at least one transparent window (e.g., window 164) located between the light source and the article. In some embodiments, light source 160 may be configured to emit light in the ultraviolet (UV), the visible or the infrared (IR) spectrums. In some embodiments, controller 150 may be configured to control the provision of light from light source 160.

[0081] Some nonlimiting examples for light source 160 may include an array of light-emitting-diodes (LEDs), discharge lamps, halogen lamps, and incandescent light bulbs and the like.

[0082] In some embodiments, system 100 may further include a diffuser 162 configured to diffuse the light over the article. In some embodiments, system 100 may further include a transparent window 164 allowing light to enter chamber 110.

[0083] An article fabrication system 101 illustrated in Fig. 1B may include substantially the same elements as article fabrication system 100. In some embodiments, article fabrication system 101 may further include at least one imaging device 170 configured to capture light transmitted through, or reflected from, the curable liquid. The light may be illuminated from

imager light source 175. In such case at least one light source 160 (e.g., LED array) may include a gape/opening 172 allowing light from imager light source 175 to travel to at least one imaging device 170. In some embodiments, at least one imaging device 170 may be selected from, a camera and a wavefront sensor. In some embodiments, controller 150 may be configured to: receive an image from the at least one imaging device; and control at least one of, the curable liquid provision unit, the immersion liquid hydraulic system, and the at least one light source, based on the image.

[0084] Some additional aspects of the invention may include a kit for article fabrication. The kit may include the article fabrication system 100 according to any one of the embodiments disclosed herein; the immersion liquid; and the curing liquid.

[0085] Reference is now made to Figs. 2A, 2B, and 2C, which are illustrations and a flowchart of steps in a method of fabricating an article according to some embodiments of the invention. The method may be performed by system 100 under the supervision of controller 150 or any other controller.

[0086] In step 210, an immersion liquid may be provided to at least one first portion and at least one second portion of a chamber divided by a divider. In some embodiments, controller 150 may control immersion liquid hydraulic system 130 to provide immersion liquid to chamber 110, from an immersion liquid reservoir (not illustrated). For example, immersion liquid pump 134 may pump immersion liquid from the reservoir to be provided to first portion 112. Since at this stage the opening in divider 120 is still open, second portion 114 may also be filled with the immersion liquid.

[0087] In step 220, a valve may be opened between the at least one first and at least one second portions. In some embodiments, controller 150 may control valve 132 to allow pressure equalizing between first portion 112 and second portion 114, as long as valve 132 is open. Steps 210 and 220 are illustrated in the first illustration in Fig. 2A.

[0088] In step 230, a curable liquid may be provided to an article frame included in the divider. In some embodiments, controller 150 may control curable liquid provision unit 140 to provide the curable liquid to article frame 122 of divider 120. For example, pump 144 may pump a predetermined amount of curable liquid from a curable liquid reservoir and inject/insert the curable liquid to article frame 122 via port 142. When provided to frame 122 the curable liquid fills the entire frame due to capillary forces, thereby closing the opening in divider 120 and frame 122. At this stage first portion 112 is separated from second

portion 114, which remain connected only by valve 132. As long as valve 132 remains open the pressure of the immersion liquid in both first portion 112 and second portion 114 is equalized. Step 230 is illustrated in the second illustration in Fig. 2A.

[0089] In step 240, the valve may be. For example, controller 150 may close valve 132, thereby completely separating first portion 112 from second portion 114. Due to the sealing (e.g., by gasket 128) no immersion liquid can leak from first portion 112 to second portion 114 or *vice versa*.

[0090] In step 250, a volume or pressure of the immersion liquid may be adjusted in the at least one first portion using a pump, to control a curvature of the article. For example, controller 150 may control pump 134 of immersion liquid hydraulic system 130 to increase the pressure/volume of the immersion liquid in first portion 112 by adding immersion liquid to first portion 112, as illustrated in steps 240 and 250 of Fig. 2A. In such a case, a concave curvature may form in the curable liquid. Alternatively, controller 150 may control pump 134 of immersion liquid hydraulic system 130 to decrease the pressure/volume of the immersion liquid in first portion 112 by extracting immersion liquid from first portion 112. In such a case, a convex curvature may form in the curable liquid.

[0091] In step 260, only illustrated in Fig. 2A, the curable liquid may be cured to form the article. For example, controller 150 may control light source 160 to illuminate the curable liquid, with one of: UV light, IR light or visible light, thereby hardening the curable liquid to form article 200. In some embodiments, simulation to curing the curable liquid the volume or the pressure of the immersion liquid may be adjusted in the at least one first portion during curing. This may be done to eliminate any undesired pressure that may be applied to the curable liquid during curing, that may deform the article during curing. In some embodiments, the adjustment may be done passively by releasing access immersion liquid if the pressure in first portion 12 exceeds a predetermined threshold, and/or done actively by operating pump 134 to adjust the volume or the pressure of the immersion liquid in the at least one first portion.

[0092] In step 270, only illustrated in Fig. 2A, the article may be taken out from the immersion fluid and optionally also from frame 122, as illustrated in Fig. 2C.

[0093] In the nonlimiting example of Fig 2C article 200 is an optical article, more specifically lenses for glasses. In the non-limiting example, article 200 is made from an optical grade polymer and has a curvature to fit a prescription from an optometrist. In some

embodiments, the precise curvature may be determined based on at least one of: one structure of farm 122, as discussed herein below, the adjustment of the pressure/volume of the immersion liquid in portion 112, the amount of curable liquid, and the ratio between the densities of the immersion liquid and the curable liquid.

[0094] Some additional aspects of the invention are directed to a frame for manufacturing an article, for example, frame 122. Frame 122 may include an enclosure 121 (illustrated in Fig. 3) having a wall with variable heights along the enclosure's contour.

[0095] Reference is now made to Fig. 3 which includes illustrations of a model of a frame and the frame for fabricating an article according to some embodiments of the invention. In some embodiments, the variability of the height is determined based on an intersection of the enclosure's contour 121 with a surface 123 having a desired topography of the article.

[0096] In some embodiments, the design of frame 122 may have an arbitrary footprint based on a theoretical curable liquid as discussed herein above with respect to Equations 1 to 1.6. In some embodiments, a theoretical circular article may be considered, for example, an optical lens with a desired prescription, whose dimensions are larger than desired frame 121. The article can be described by two surfaces $h_{top} = h_{top}(x, y)$ and $h_{bot} = h_{bot}(x, y)$, and the distance between them. Therefore, the two surfaces may be described analytically as a function of the frame's shape and as a function of the theoretical volumes V_{lens}, V_{add} (the volume of the curable fluid and the volume injected to the bottom of the aquarium).

[0097] In some embodiments, frame 121 whose planar footprint is described by the set of coordinates (x_F, y_F) (as illustrated in Fig. 3), the two edges of the required frame are given by $z_{top} = h_{top}(x_F, y_F)$, $z_{bot} = h_{bot}(x_F, y_F)$, as illustrated. Frame 121 wall is then defined by an intersection of surface 123 with edges z_{top} and z_{bot} , as illustrated.

[0098] For example, the desired topography may satisfy the fluidic shaping Equation 1 or Equation 1.6, discussed above. In another example, the desired topography may be defined as the surface that is the result of injecting the curable liquid into frame 122.

[0099] In some embodiments, enclosure's contour 121 is determined based on a receiving device, receiving article 200, and illustrated in Fig. 2C. In a nonlimiting example, article 200 is a lens or a mirror, and the receiving device is selected from eyewear frame 210 (as illustrated), microscopes, telescopes, binoculars, and laser cavities. In some embodiments, farm 122 is an integral part of receiving device 210. In a nonlimiting example, the entire

receiving device (e.g., eyewear frame) may be inserted to article fabrication system 100 and may be held by divider 120, therefore article 200 may be fabricated directly in a frame integrally included in receiving device 210. In a nonlimiting example, eyewear frame may be inserted into article fabrication system 100 and each one of the lenses may be fabricated by system 100 directly into frames 122 of eyewear frame 210.

[00100] Reference is now made to Fig. 4 which shows simulations of frames and articles (e.g., lenses) according to some embodiments of the invention. In order to have a correct shape of the article, a specific frame 122A or 122B is tailored. A non-circular frame with incorrect height values may result in undesired variations in spherical and cylindrical power of the desired topography. Fig. 4 shows two lenses that can be fabricated under the same conditions with frames having the same (x_F, y_F) coordinates and equal injected volume. A right frame 122B has a 'naïve' design with uniform height, while a left frame 122A has variable heights based on a method according to embodiments of the invention. Using frame 122B made with the uniform height frame for fabricating an article may result in an article 200B exhibiting significant non-uniformity in the spherical power and high cylinder values. Using frame 122A having varying height according to embodiments of the invention, may result in an article 200A with a uniform spherical power and cylinder values.

[00101] Reference is now made to Fig. 5 which shows illustrations of additional two frames and the corresponding lenses fabricated using these frames according to some embodiments of the invention. In some embodiments, at least a portion of a surface of frames 122 and 122A may create a connector for connecting at least one of, the frame and the article, to the receiving device. In some embodiments, an inner surface of frames comprising 122 and 122A may include at least one element 125 and/or 127. In some embodiments, at least one element 125 and/or 127 is configured to form a connector for connecting at the article, to the contour of a space in the receiving device. For example, at least one element may be a recess 125 and/or a protrusion 127 located on the inner surface of the wall of frame 122 (as illustrated). Therefore, if frame 122 is removed from article 200, the article may be inserted into the space in the receiving device 210 (e.g., eyewear frame) as illustrated. Alternatively, frame 122 may remain attached to article 200, and therefore, at least one connecting element 125 and/or 127 may be located on the outer surface of frame 122. In such case frame 122 holding article 200 may be inserted into the space in the receiving device 210.

[00102] Reference is now made to Fig. 6, which is a flowchart of a method of making a frame for manufacturing an article. The method of Fig. 6 may be performed by any computer aided manufacturing platform, such as, additive manufacturing platform (e.g., 3D printing), CNC milling machines, and the like. The method of Fig. 6 may be performed on-site, in a point of sell, for example, in an optometry shop.

[00103] In step 610, a contour of a receiving device may be received. For example, a controller of the any computer aided manufacturing platform may receive contour of an article from a user via a user device/user interface. The contour may be selected from a list of known contours (e.g., a list of eyewear frames) or may be received from image analysis of an image of the frame.

[00104] In step 620, an enclosure contour of the frame may be determined to fit the contour of a space in the receiving device. For example, mathematical functions determining the edges of frame 122 may be given by $z_{top} = h_{top}(x_F, y_F)$ and $z_{bot} = h_{bot}(x_F, y_F)$ as illustrated and discussed with respect to Fig. 3. In some embodiments, the controller may determine the mathematical functions, for example, by using a lookup table associated with the list of known contours, from the image analysis and the like.

[00105] In step 630, a desired topography of the article may be received. For example, the desired topography may be received from a user, using a user device or a user interface. In some embodiments, the desired topography may satisfy Equation 1 or Equation 1.6. In a nonlimiting the desired topography may be determined based in an optical prescription.

[00106] In step 640, heights of a wall of the enclosure, along the contour may be determined based on an intersection of the enclosure's contour with a surface having the desired topography, for example, as illustrated and discussed with respect to Fig. 3.

[00107] In step 650, the enclosure wall may be fabricated to form the frame. For example, the manufacturing unit(s) of the computer aided manufacturing platform may fabricate frame 122 using at least one of, additive manufacturing (e.g., 3D printing), machining, milling, grinding, and the like.

[00108] In some embodiments, the method may include adding at least one external connecting element to an outer surface of the frame, wherein the at least one external connecting element is configured to form a connector for connecting at least one of the frame and the article to the contour of the space in the receiving device, as discussed with respect to Fig. 5.

Examples

[00109] An analytical model was developed. The analytical model relates the desired optical prescription to the geometrical parameters required for the fabrication of the lens according to some embodiments of the invention. An illustration of an elliptic lens and the analytical results of the optical powers of the fluidic lens as a function of the frame geometry and the injected volumes, according to some embodiments of the invention, are given in Figs. 7A, 7B, 7C, and 7D.

[00110] Fig. 7A shows a schematic illustration of a fluidic lens formed within a frame of height t , consisting of a circular bottom contour of radius R_0 and an elliptical top contour with semi diameters a, b . The volume of the liquid hardening material encompassed within the frame is V_{lens} and the volume enclosed between its bottom surface and the x-y plane is V_{enc} . At steady state, the system achieves its minimum energy configuration, which can be described by the minimization of an energy functional for the top and bottom surface minimization of an energy functional for the top and bottom surface $h_{top}(x,y)$ and $h_{bot}(x,y)$.

[00111] In this nonlimiting example, the bottom surface was guaranteed to be a spherical cap with a radius of curvature denote as R_{bot} , and the top surface is a toric surface with two radii of curvature, $R_{x_{top}}$ and $R_{y_{top}}$. The spherical power of such a lens is given by the 'lens maker's equation s equation 8.

$$P = (n-1) \left(\frac{1}{R_{top}} - \frac{1}{R_{bot}} + \frac{(n-1)d}{nR_{top}R_{bot}} \right) \quad (8)$$

where $R_{top} = (1/R_{x_{top}} + 1/R_{y_{top}})^{-1}$ is the mean radius of curvature of the top surface, d is the center thickness of the lens, and n is the reflective index of the hardening liquid.

[00112] Similarly, the cylindrical power is given by equation 9.

$$C = (n-1) \left(\frac{1}{R_{x_{top}}} - \frac{1}{R_{y_{top}}} \right) \left(1 + \frac{(n-1)d}{nR_{bot}} \right) \quad (9)$$

[00113] Using the minimum energy model, the radii of curvature can be related to the geometry of the frame and the injected volume of the hardening liquid. Through the thin

lens approximation, the spherical and cylindrical powers can be expressed by equations 10(a) and 10(b).

$$\begin{aligned} \text{(a)} \quad P &= 2(n-1) \left(\frac{(\Delta V_{lens} + V_{enc})(a^2 + b^2)}{\pi a^3 b^3} - \frac{h_0}{R_0^2} \right), \\ \text{(b)} \quad C &= 4(n-1) \frac{(\Delta V_{lens} + V_{enc})(a^2 - b^2)}{\pi a^3 b^3}, \end{aligned} \quad (10)$$

where $\Delta V_{lens} = V_{lens} - \frac{\pi}{2}(a+b)R_0 t$, and $h_0 = \frac{2V_{enc}}{\pi R_0^2}$ is the clearance distance between the x-y

plane and the center of the bottom surface, as illustrated in Fig. 7A.

[00114] Combining equations 10(a) and 10(b), may lead to equation 11

$$P = C \cdot \left(\frac{1}{e^2} - \frac{1}{2} \right) - 2(n-1) \frac{h_0}{R_0^2} \quad (11)$$

indicating that any combination of spherical and cylindrical powers can be achieved by adjusting the eccentricity of the of frame, $e = \sqrt{1 - (\frac{b^2}{a^2})}$.

[00115] The cylindrical power as a function of the spherical power and the eccentricity is shown in Fig. 7B, for lens with $R_0 = 25mm$, $n = 1.525$ and $h_0 = 3mm$. Fig. 7B demonstrates the degrees of freedom in the design, where for a lens of a given radius R_0 and a desired clearance h_0 , one can select the desired spherical power, and obtain the required eccentricity in order to satisfy the desired cylindrical power. Using equations 10(a) and 10(b) the hardening liquid volume ΔV_{lens} , required to produce the lens. The flowchart in Fig. 7E may be used for determining the physical parameters (frame geometry and liquid volumes) required to achieve any spherical and cylindrical combination.

[00116] The hardening liquid volume ΔV_{lens} as function of the lens's size is given in Fig. 7C, for the simplified case of zero cylindrical power. The displayed values encompass

typical sizes for children's and adults' frames but, can naturally be extended beyond the presented range. The typical volume to be injected is on the order of milliliters. The curve in the figure shows the sensitivity of the diopter to inaccuracy in the injection. For example, for a 50 mm frame diameter, a 1/8 diopter deviation (which is well within the range that the human eye typically cannot discern), results from a 50 μ l inaccuracy in volume. Maintaining such a volume accuracy, on the order of 1% total volume, can be easily achieved with low-cost injection systems.

[00117] Contrary to the spherical power, which is dictated by the difference in curvature between the top and bottom surfaces and thus is weakly affected by V_{enc} , the cylindrical power is controlled only by the elliptic (top) surface and is thus much more sensitive to both ΔV_{lens} and V_{enc} .

[00118] Fig. 7D shows the cylindrical power of the lens as a function of eccentricity and the total volume $\Delta V_{lens} + V_{enc}$, for a base diameter of 50 mm and a refractive index 1.525. The blue curve describes the cylindrical power sensitivity to the combined injected volumes, which is an order of magnitude lower than that of the spherical power. The curve represents the cylindrical power sensitivity to variations in eccentricity, for two injection volumes, 3ml (typical) and 6 ml (extreme). For lenses with no cylindrical power, the sensitivity to variations in eccentricity is most significant. Even in this extreme case, the diameters (a or b) may vary by as much as 300 μ m and still remain within a 1/8 diopter variation. This sensitivity decreases significantly with the increase in nominal cylindrical power.

[00119] Reference is now made to Fig. 7E which is a flowchart of a method for calculating the frame geometry and liquid volumes needed for fabricating a desired lens according to some embodiments of the invention. In step 710, the method may include receiving the required input parameters, which include the spherical power (P), the cylindrical power (C), the desired size of the lens (R_0), the clearance from the eye (h_0), the refractive index (n) of the polymer liquid, and for negative lenses- the allowed lens thickness (d). In some embodiments, for positive lenses, the parameters may further include the frame thickness (t).

[00120] In step 720, the method may include calculating the frame's eccentricity using the term $P = C \cdot \left(\frac{1}{e^2} - \frac{1}{2} \right) - 2(n-1) \frac{h_0}{R_0^2}$. This calculation may yield the elliptical boundary

semi diameters (a , b). Step 720 may further include, calculating the volume enclosed under the lens' bottom surface, V_{enc} , using Equation 12.

$$h^{(b)} = \frac{2V_{enc}}{\pi R_0^2} \left(1 - \frac{r^2}{R_0^2} \right). \quad (12)$$

[00121] In step 730, the method may include calculating ΔV_{lens} using Equation (13).

$$C = 4(n-1) \frac{(\Delta V_{lens} + V_{enc})(a^2 - b^2)}{\pi a^3 b^3} \quad (13)$$

[00122] In step 740, the method may include calculating the total volume of immersion liquid that should be injected, $V_{imm} = \frac{1}{2} \Delta V_{lens} + V_{enc}$ using the immersion liquid volume (V_{enc}), and the value of ΔV_{lens} .

[00123] In step 750, the method may include, for negative spherical power lenses, calculating the height of the bounding frame using Equation (14); and for positive spherical power, this value is one of the inputs.

$$\begin{aligned} \frac{1}{R_{x,top}} &= \left| \frac{h_{xx}^{(t)}}{\left(1 + \left(h_x^{(t)}\right)^2\right)^{3/2}} \right| = \frac{4(V_{lens} + V_{enc} - V_{frame})}{\pi a^3 b} \\ \frac{1}{R_{y,top}} &= \left| \frac{h_{yy}^{(t)}}{\left(1 + \left(h_y^{(t)}\right)^2\right)^{3/2}} \right| = \frac{4(V_{lens} + V_{enc} - V_{frame})}{\pi a b^3} \\ \frac{1}{R_{top}} &= \frac{1}{2} \left(\frac{1}{R_{x,top}} + \frac{1}{R_{y,top}} \right) = \frac{2(V_{lens} + V_{enc} - V_{frame})}{\pi a^3 b^3} (a^2 + b^2) \quad (14) \\ \frac{1}{R_{bot}} &= \left| \frac{h_{rr}^{(b)}}{\left(1 + \left(h_r^{(b)}\right)^2\right)^{3/2}} \right| = \frac{4V_{enc}}{\pi R_0^4} \\ d &= h^{(t)}(0,0) - h^{(b)}(0) = t + \frac{2}{\pi} \left(\frac{(V_{lens} + V_{enc} - V_{frame})}{ab} - \frac{V_{enc}}{R_0^2} \right). \end{aligned}$$

[00124] In step 760, the method may include calculating the volume of polymer liquid that should be injected, V_{lens} , using the frame geometry, ΔV_{lens} , and the enclosed immersion liquid volume, V_{enc} .

[00125] In step 770, the method may include receiving the frame geometry a, b, t and the required volumes V_{lens}, V_{imm} .

[00126] Reference is now made to Figs. 8A, 8B, 8C and 8D which are experimental results and characterization of eyewear lenses fabricated using the fluidic shaping method according to some embodiments of the invention. Fig. 8A shows the normalized diopter, $\tilde{P} = P \cdot (\pi R^4) / (4(n-1))$, as a function of the injected polymer volume, for 92 lenses fabricated using circular frames, spanning both negative and positive diopters, for two frame diameters, and for two different polymers – one UV curable, and one thermally cured. The error bars in the horizontal direction represent an uncertainty in ΔV_{lens} , which propagates from uncertainties in the injection volume and in the frame dimensions. The power value represents the average power over the entire area of the lens, measured by a Moiré deflectometer (Mapper, Rotlex, Israel). The results are in good agreement with calculations (the straight solid line) made using equations 1.9a and 1.9b, where $a=b=R_0$, and demonstrate the ability to design and fabricate lenses covering a wide range of optical powers (here between $P=-6$ and $P=5$ diopters).

[00127] For a given fabricated lens, the quality is determined by the uniformity of the optical power over its area. Figs. 8B and 8C present the deviation of the measured spherical and cylindrical power distributions from their expected theoretical values, for two good-quality lenses produced using Fluidic Shaping. The images in Fig. 8B correspond to a lens produced in a circular frame ($e = 0, R_0 = 25mm$), i.e., intended to have a purely spherical correction.

[00128] The spherical power in this case deviates by 0.11 diopters (D) from the intended value and the spatial standard deviation is 0.04 D. The lens shows a residual cylindrical power of 0.17 D, with a standard deviation of 0.1D. The cylindrical deviation was within the commonly acceptable spec, based on the human eye sensitivity, and the spherical deviation meets an even more stringent spec of $< 1/8$ D.

[00129] The images in Fig. 8D correspond to a lens produced in an elliptical frame ($e = 0.552, a = 30mm, b = R_0 = 25mm$), with an injected liquid volume designed to obtain the same spherical diopter as in Fig. 8D, but with a distinct cylindrical diopter of 1.7 D. This illustrates the ability to independently define the two nominal powers. Here, too, the

standard deviation for both powers is within the commonly acceptable ranges. An additional important criterion by which optical components are assessed is their surface roughness - lenses with poor surface quality cannot be functionally used. Figure 4d presents an AFM measurement showing an average surface roughness of 1.4 nm in a measurement area of $3\mu\text{m} \times 3\mu\text{m}$. The measurements were performed at 9 different locations, on 4 different lenses. As expected, since surface roughness is dictated by surface tension and the molecular structure of the polymer, the result is independent of the location or the shape of the lens. In a total of 9 measurement sites, the root-mean-squared (RMS) values were ranging between 0.43 nm and 3.3 nm, with an average value of 1.4 nm. These values are between one and two orders of magnitude better than the industry standard which is tens of nanometers.

[00130] Unless explicitly stated, the method embodiments described herein are not constrained to a particular order or sequence. Furthermore, all formulas described herein are intended as examples only and other or different formulas may be used. Additionally, some of the described method embodiments or elements thereof may occur or be performed at the same point in time.

[00131] While certain features of the invention have been illustrated and described herein, many modifications, substitutions, changes, and equivalents may occur to those skilled in the art. It is, therefore, to be understood that the appended claims are intended to cover all such modifications and changes as fall within the true spirit of the invention.

[00132] Various embodiments have been presented. Each of these embodiments may of course include features from other embodiments presented, and embodiments not specifically described may include various features described herein.

CLAIMS

1. An article fabrication system, comprising:
 - a chamber configured to hold an immersion liquid;
 - a divider comprising a through opening, dividing the chamber into at least one first portion and at least one second portion, the divider comprising an article frame and a gasket located between the divider and the frame;
 - an immersion liquid hydraulic system comprising at least one control valve and at least one bidirectional immersion liquid pump, wherein the immersion liquid hydraulic system is configured to:
 - allow equalization of the pressure between the at least one first portion and the at least one second portion; and
 - adjust volume or pressure of the immersion liquid in the at least one first portion;
 - a curable liquid provision unit comprising curable liquid reservoir, configured to provide curable liquid to the article frame; and
 - a controller configured to:
 - control the immersion liquid hydraulic system to equalize the pressure between the first and second portions;
 - control the immersion liquid hydraulic system to block a flow between the first and second portions;
 - control the curable liquid provision unit to provide the curable liquid to the article frame; and
 - control the immersion liquid hydraulic system to either increase or decrease the amount or pressure of the immersion liquid in the first portion.
2. The article fabrication system of claim 1, wherein the immersion liquid hydraulic system further comprises:
 - the at least one control valve is a pressure control valve fluidically connected between the at least one first portion and the at least one second portion and configured to allow equalization of the pressure between the at least one first portion and the at least one second portion,

and wherein the at least one bidirectional pump is in fluid connection with the first portion configured to control the volume or the pressure of the immersion liquid in the at least one first portion.

3. The article fabrication system of claim 2, wherein the immersion liquid hydraulic system comprises two bidirectional pumps in fluid connection with the first portion, wherein a first of the two bidirectional pumps is configured to provide a solvent solution and a second of the two bidirectional pumps is configured to provide at least one solute solution, and wherein the controller is configured to control the first and second bidirectional pumps to provide the solvent and the solute at a predetermined ratio to form the immersion liquid.
4. The article fabrication system of claim 3, further comprising a first mixer for mixing the solvent solution and the solute solution prior to the provision of the immersion liquid into the first portion.
5. The article fabrication system of claim 3, further comprising a second mixer for mixing the solvent solution and the solute solution inside the chamber.
6. The article fabrication system according to any one of claims 3 to 5, wherein the solvent solution has a density smaller than the density of the curable liquid and wherein the solute solution has a density higher than the density of the curable liquid.
7. The article fabrication system according to any one of claims 1 to 6, wherein the bidirectional pressure control valve is in fluid connection with the first portion, the second portion, and the at least one bidirectional pump.
8. The article fabrication system of any one of claims 1 to 7, wherein the curable liquid provision unit further comprises:
 - a port configured to provide curable liquid from the curable liquid reservoir to the article frame; and
 - at least one curable liquid bidirectional pump in fluid connection with the port and the curable liquid reservoir.
9. The article fabrication system of any one of claims 1 to 8, wherein the divider further comprises
 - a dividing plate having the through opening; and

a frame holder sealingly securing the gasket and the frame to the dividing ring.

10. The article fabrication system of any one of claims 1 to 9, further comprising at least one imaging device configured to capture light transmitted through or reflected from the curable liquid.
11. The article fabrication system of claim 10, wherein the at least one imaging device is at least one of, a camera and a wavefront sensor.
12. The article fabrication system of claim 10 or claim 11, the controller is configured to:
receive an image from the at least one imaging device; and
control at least one of, the curable liquid provision unit, the immersion liquid hydraulic system, and the at least one light source, based on the image.
13. The article fabrication system of any one of claims 1 to 12, further comprising:
at least one light source configured to illuminate the article.
14. The article fabrication system of claim 13, wherein the at least one light source is located at at least one of: end of the first portion opposite to the article frame, or end of the second portion opposite to the article frame, on a wall of the first portion or a wall of the second portion, and outside the closed chamber wherein the closed chamber comprises at least one transparent window located between the light source and the article.
15. The article fabrication system of claim 13 or claim 14, wherein the controller is further configured to control the at least one light source to provide light to the curable liquid.
16. The article fabrication system of any one of claims 13 to 15, wherein the light source comprises at least one of, an array of light-emitting-diodes (LEDs), gas-discharge lamps and incandescent light bulbs.
17. The optical article fabrication system of any one of claims 13 to 16, further comprising a diffuser configured to diffuse the light over the article.
18. The article fabrication system according to any one of claims 1 to 17, further comprising a pressure sensor in fluid connection with the at least one first portion, and wherein the controller is configured to control the immersion liquid

hydraulic system based also on pressure measurements received from the pressure sensor.

19. The article fabrication system according to any one of claims 1 to 18, wherein the curable liquid and said immersion liquid are immiscible.
20. The article fabrication system according to any one of claims 1 to 19, wherein the density ρ_{im} of the immersion liquid varies from the density of the curable liquid ρ by less than 15 %
21. The article fabrication system according to any one of claims 1 to 20, wherein the article is a curved article.
22. The article fabrication system according to any one of claims 1 to 21, wherein the article is an optical article and the curable liquid is at least partially transparent.
23. The article fabrication system according to any one of claims 1 to 22, wherein the article is a mold for optical fabrication.
24. A kit for article fabrication comprising:
 - the article fabrication system according to any one of claims 1 to 23;
 - the immersion liquid; and
 - the curing liquid.
25. A method of fabricating an article, comprising:
 - providing an immersion liquid to at least one first portion and at least one second portion of a chamber divided by a divider;
 - opening a valve between the at least one first and at least one second portions;
 - providing a curable liquid to an article frame included in the divider;
 - closing the valve;
 - adjusting a volume or pressure of the immersion liquid in the at least one first portion using a pump, to control a curvature of the article; and
 - curing the curable liquid to form the article.
26. The method of claim 25, further comprising receiving measurements of pressure of the immersion liquid in the at least one first portion, and
 - wherein adjusting the volume or the pressure of the immersion liquid in the first portion is done based on the pressure measurements and required characteristics of the article.

27. The method of claim 25 or claim 26, wherein curing the curable liquid comprises adjusting the volume or the pressure of the immersion liquid in the at least one first portion during curing.
28. The method of claim 27, wherein adjusting comprises one of: passively releasing access immersion liquid if the pressure in the first portion exceeds a predetermined threshold, and actively operating the pump to adjust the volume or the pressure of the immersion liquid in the at least one first portion.
29. The method according to any one of claims 25 to 28, wherein the article is a curved article.
30. The method according to any one of claims 25 to 29, wherein the article is an optical article and the curable liquid is at least partially transparent.
31. The method according to any one of claims 25 to 30, wherein the article is a mold for optical fabrication.
32. A frame for manufacturing an article, comprising:
 - an enclosure having a wall with variable heights along the enclosure's contour.
33. The frame of claim 32, wherein the enclosure's contour is determined based on a receiving device, receiving the article.
34. The frame of claim 33, wherein the article is a lens or a mirror, and the receiving device is selected from eyewear frame, microscopes, telescopes, binoculars, and laser cavities.
35. The frame of any one of claims 32 to 34, wherein the frame is an integral part of the receiving device.
36. The frame of any one of claims 32 to 35, wherein the variability of the height is determined based on an intersection of the enclosure's contour with a surface having a desired topography of the article.
37. The frame of claim 36, wherein the desired topography of the surface satisfies the following fluidic shaping equation:

$$\frac{r^2 h_{rr} \left(1 + \frac{1}{r^2} h_{\theta}^2\right) + (r h_r + h_{\theta\theta}) (1 + h_r^2) - 2 h_{\theta} h_r h_{r\theta} + \frac{2}{r} h_r h_{\theta}^2}{\left(1 + h_r^2 + \frac{1}{r^2} h_{\theta}^2\right)^{3/2}} = \pm (Ah+B) r^2$$

wherein r is a normalized radius variable, h is a normalized surface height variable, subscripts denote spatial derivatives of h with respect to a radial direction or to an azimuthal direction, and A and B are free parameters.

38. The frame of any one of claims 31 to 36, wherein at least a portion of a surface of the frame creates a connector for connecting at least one of, the frame and the article, to the receiving device.
39. The frame of claim 37, wherein an inner surface of the frame comprises one or more connector forming elements, thereby forming at least one connector on a contour of the article for connecting the article to the receiving device.
40. The frame of claim 38, wherein the at least one connector forming elements are selected from, a recess and a protrusion and any combination thereof.
41. The frame of claim 37, wherein an outer surface of the frame comprising the connector for connecting the frame to the receiving device.
42. A method of making a frame for manufacturing an article, comprising:
 - receiving a contour in a receiving device;
 - determining an enclosure contour of the frame to fit the contour in the receiving device;
 - receiving a desired topography of the article;
 - determining heights of a wall of the enclosure, along the contour based on an intersection of the enclosure's contour with a surface having the desired topography; and
 - fabricating the enclosure wall.
43. The method of claim 41, further comprising adding at least one external connecting element to an outer surface of the frame, wherein the at least one external connecting element is configured to form a connector for connecting at least one of the frame and the article to the contour of the space in the receiving device.
44. The method of claim 41 or claim 42, wherein the desired topography of the surface satisfies the following fluidic shaping equation

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$$\frac{r^2 h_{rr} \left(1 + \frac{1}{r^2} h_\theta^2 \right) + (r h_r + h_{\theta\theta}) (1 + h_r^2) - 2 h_\theta h_r h_{r\theta} + \frac{2}{r} h_r h_\theta^2}{\left(1 + h_r^2 + \frac{1}{r^2} h_\theta^2 \right)^{3/2}} = \pm (Ah+B) r^2$$

wherein r is a normalized radius variable, h is a normalized surface height variable, subscripts denote spatial derivatives of h with respect to a radial direction or to an azimuthal direction, and A and B are free parameters.