Some milestones in the design, development, and manufacture of freeform optics

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ABSTRACT

Freeform optics are lenses or mirrors with surfaces having no rotational symmetry. They were conceived more than a century ago, but have recently received new attention for solving design problems. The special methods needed to manufacture them have included direct cam driven or digital grinding or milling, hot glass sagging, casting, injection molding, and fast-tool diamond turning. More recently, precision 3D printing and nano-crystalline powder compression molding have offered promising new capabilities for inexpensive high-volume commercial production in the future. Applications of freeform optics have included progressive spectacle lenses, focus adjusting devices, and aperture phase masks for special purposes. These design applications and manufacturing capabilities have been related to each other in interesting ways, and will be illustrated through a selection of patents and photographs of commercial products.

KEY WORDS: Freeform, molding, spectacles, infrared, 3D printing

INTRODUCTION

Freeform optical surfaces were suggested more than 100 years ago for use on spectacle lenses. There were early patents by Aves[1] in England and Poulain and Cornet[2] in France. Many years passed before freeform surfaces became available. There were two patents by Evans[3,4] in the USA, first proposing a freeform spectacle design and later a suggestion for manufacturing it. I don't know whether any on these lenses were actually made.

In 1959 Clarence Kanolt[5] described the mathematics useful for making a good image with a freeform spectacle lens, and disclosed that the freeform progressive surface and the prescription surface for correcting astigmatism could be combined on one side of the lens by simple addition of the shapes. At about this time Maitenaz[6,7] in France designed the first commercially successful freeform spectacles.

In the last decades freeform optical surfaces have found many other uses beyond their beginning in spectacle lenses.

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FREEFORM OPTICS USED IN CAMERA VIEWFINDERS

Polaroid SX-70 Land camera

The Polaroid SX-70 camera was introduced to the public in 1972 by Edwin Land, depicted on a LIFE magazine cover[8]. This unusual camera was the first commercial product, other than eyeglasses, to make use of freeform optical surfaces. The SX-70 camera, shown cut away, was a single-lens-reflex. The photographer saw the scene and composed his picture while looking through the lens of the camera itself. The large shiny area near the bottom is a reflective Fresnel focus screen, textured[9] to provide optimum focus performance for the f/8 objective lens. Figure 1 shows the camera with one side of it cut away to reveal the interior.

Figure 1. The Polaroid SX-70 Land camera, first sold in 1972.

LIFE Magazine[8] included a cross section photograph of the SX-70 camera, page 44, showing three colors of light passing through all of the viewing optics. Light coming from three different directions in a scene -- high, middle, and low -- passes through the picture taking lens on the left. It all reflects from a flat mirror, and then forms three separate images on the focus screen at the bottom. The focus screen is a reflecting Fresnel mirror that brings the three colors together again, reflects them once more from the flat mirror, and directs all of them out of the camera body through one small hole, an aperture stop, near the top of the mirror. Then the three colors spread apart, reflect from a molded concave mirror, and form three separated images in the air. The three colors continue into a molded eye lens, and are brought together again where they reach the photographer's eye.

The photographer sees the three color images as they appear in space in front of the camera -- high, middle, and low -- just as they will appear in the photograph. If the concave mirror were made with a usual spherical surface, the view of the square image area would appear distorted, with the upper part squeezed downward out of shape. To correct the appearance to a square, the concave mirror is designed with a non-spherical shape, becoming flatter toward the top.

Figure 2 shows the path of light through the viewing optics by little arrows. When we made the concave mirror flatter toward its top, the image of the scene formed in the air became tilted, shown by the dotted shape. As a result it formed closer to the eye lens at the top, and the eye saw it as very near. The bottom of the image appeared to be distant. A photographer with presbyopia could not see all of the image area clearly. This is the same problem that is solved in a spectacle lens with a bifocal addition, or with a progressive freeform shape. For the SX-70 camera I solved this new problem by putting a freeform shape on the flatter side of the eye lens.

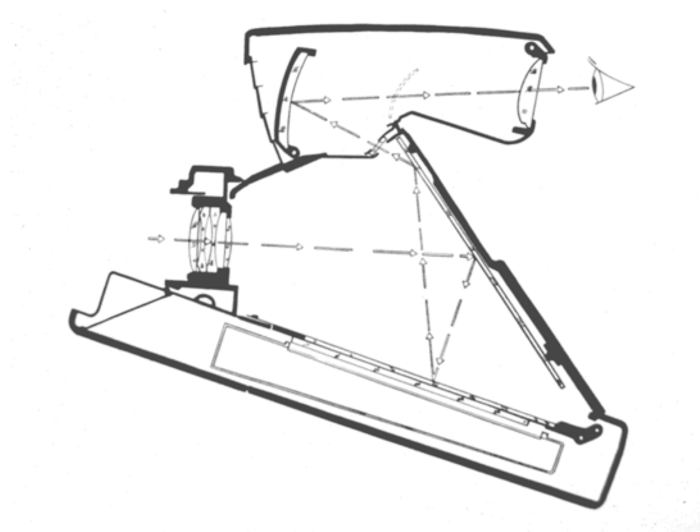

Figure 2. Path of light through the SX-70 camera in the viewing mode.

The freeform shape

To explain what a freeform shape is I made a little demonstration, shown in Figure 3. It is a flat plastic window with a thin plastic kitchen membrane stretched across it and held at the edges. I put water in it, and showed that it would make a kind of lens with both concave and convex shapes when I tilted it. This shape has no axis of rotational symmetry.

Figure 3. A demonstration freeform lens formed with a stretched membrane and water.

Two patents[10,11] showed where the freeform shape was placed on the eye lens. Figure 4 illustrates the shape we used, with the dimension exaggerated to show its form. The size of this surface is about 2 centimeters square, a little smaller than a spectacle lens.

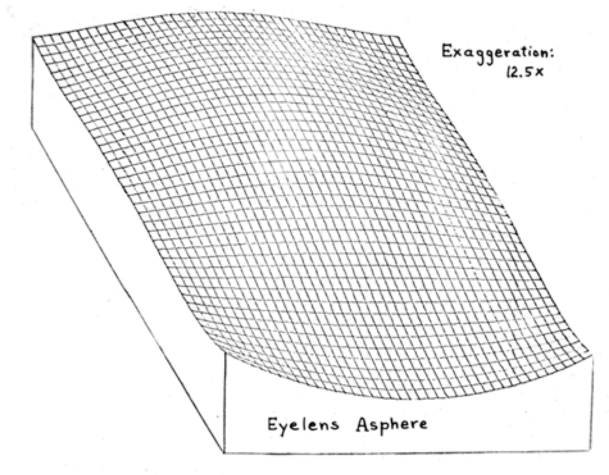

Figure 4. Freeform shape applied to the eye lens of the SX-70 camera.

Freeform mold tooling

We made metal injection mold tooling for the eye lens shape by grinding it with a three-axis computer tape controlled machine, manufactured by the Boston Digital Corporation. When a surface is ground in this way, the path of the grinding tool is different from the shape of the lens surface, and has to be calculated. Where the ground surface is convex, the radius of the cutter is added to it to calculate the path, and where the ground surface is concave, the radius of the cutter is subtracted from it. Of course, this correction must be made in three dimensions.

Figure 5 is a finished molding tool made in this way, showing by reflection that it is a freeform surface. We started putting the freeform shape in the SX-70 camera in 1973.

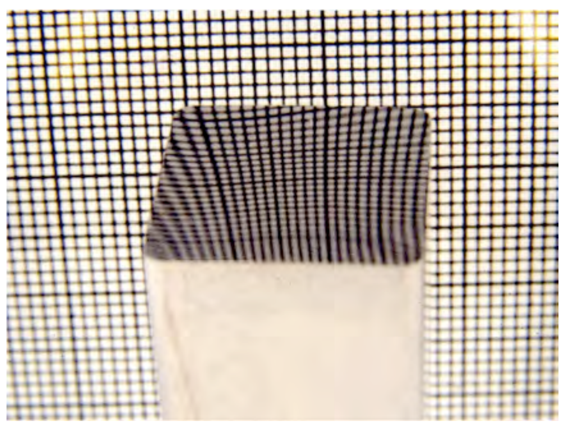

Figure 5. A finished freeform molding tool for manufacturing the eye lens of the SX-70 camera.

To measure this freeform shape and control its quality we used a profilometer to measure the molding tool and the molded lens along seven parallel paths, with a precision of about three millionths of an inch. That is only 76 nanometers. For our analysis we looked at the data in moving groups of nine points, shown here by the dark marks.

In each group of nine measurements I calculated the local curvatures in this way, giving three second derivatives of the surface shape. I then used the formulas disclosed by Kanolt in his 1959 patent[5], column 3, line 63, through column 5, line 37, to express our surface quality in ophthalmic language, stated as local spherical error and cylindrical error. In this way we controlled our camera viewing lenses within ophthalmic tolerances.

An additional design requirement for the freeform viewfinder

Our freeform eye lens shape gave us another new problem, however. Because of the changing power over the eye lens surface, the focus had to be a little different between the top and the bottom of the pupil of the eye. The concave mirror's changing shape added to this problem, called "coma", and we did not like the result.

We corrected it by introducing another little lens right at the small aperture where the light all passes from the camera body into the viewfinder, just before the concave mirror. This little lens also has a freeform shape. Since this little lens is imaged onto the pupil of the eye by the concave mirror and the eye lens acting together, we can think of it as a virtual contact lens! Baker[12] described our final optical design, showing the shape of that little lens that corrects the coma. The lens diameter is about 4 millimeters.

The eye lenses were molded 24 at a time, the small corrector lenses were molded 12 at a time, the concave mirrors were molded 32 at a time, and all of them were already polished when they were taken out of the machine. Figure 6 displays the viewing optical parts from the SX-70 camera: a mounted freeform eye lens, a mounted concave mirror, and three samples of the small freeform coma correcting lens[13].

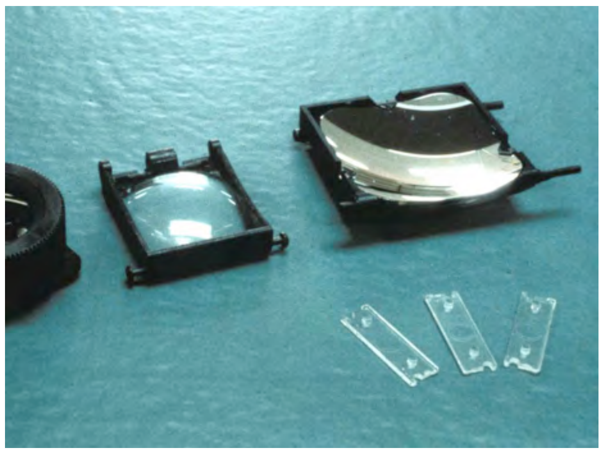

Figure 6. The molded and mounted viewfinder parts of the SX-70 camera.

A related spectacle lens design

We realized that the freeform surface we first used on the SX-70 camera could also be used on a spectacle lens if we turned it upside down, and it could be combined with other prescription requirements onto just the concave side of the lens, leaving the convex side spherical[14].

Polaroid Vision camera

We used freeform viewfinder shapes again in another product, called the Vision camera, in 1992, disclosed by Baker[15]. This later camera was also a single lens reflex, but its optics were quite different. The Vision camera had an interesting mechanical structure that used a six-bar linkage to unfold three sections in sequence as it was opened for use.

Unlike the SX-70 camera, the Vision camera did not have a focus-screen texture[9] on its Fresnel mirror surface because the focus setting was automatic. The folded viewing optical path shown in Figure 7 did not have room for an intermediate aperture stop or for the small coma correcting lens we had used in the SX-70. Instead, we used a freeform shape for the concave mirror as well as for an eye lens.

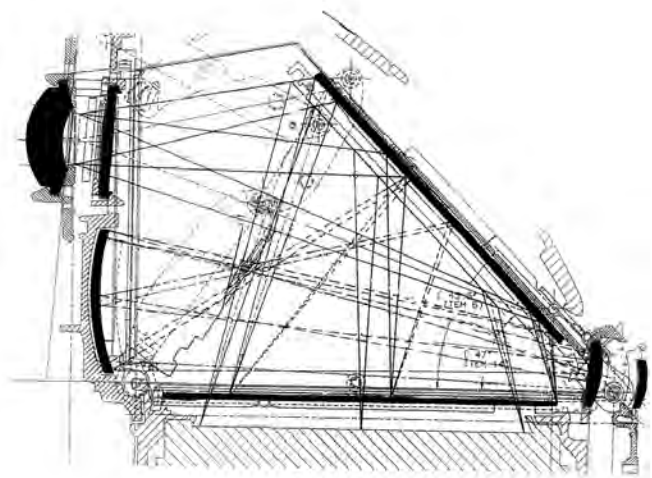

Figure 7. The path of light through the folded viewing optics of the Vision camera. The eye is at the lower right.

We ground the freeform molding tool for the concave mirror with a five-axis commercial computer controlled machine, made by Boston Digital Corporation in 1983. The smoothness tolerance for a reflective optical surface is tighter than for a refractive surface by a factor of four or more.

FREEFORM SPECTACLE LENS DESIGN AND MANUFACTURE

The first modern machine capable of generating a progressive freeform surface, including prescription correction, on just the concave side of a spherical spectacle lens blank, was disclosed by Logan and Rich at Gerber Scientific Products, in their patent[16] issued in 1991. They used a spherical milling or grinding tool, moved across a spinning lens blank by digital control. Similar or related machines were then made by several other companies.

Tom Dow disclosed a method and apparatus for forming a freeform optical surface by diamond turning on a lathe, with fast piezoelectric components used to drive the cutting tool in synchrony with the rotation[17].

In 1996 Brennan patented a machine much like Logan's, but using a diamond point instead of a spherical milling or grinding tool, to provide a more nearly finished freeform optical surface[18].

In 1998 the Schneider company introduced their HSC 100 machine[19], with both a toroidal milling cutter and a diamond point cutter that were used sequentially under digital control for producing freeform surfaces on spectacle lens blanks, needing only a final gentle polish to remove the cutting marks. The most recent version of this machine is the HSC Smart X.

In 2001 Mukaiyama and Kato of Seiko[20] and Hof and Hanssen of Zeiss[21] were issued patents for similar spectacle lens designs. Both used a spherical convex surface and combined a freeform progressive surface with any required prescription correction together on the concave side. There were some differences in their claims, including an undisclosed process of optimization in the Zeiss patent. Their concept of a spectacle lens with a spherical convex surface and combined concave freeform progressive and prescription surface had been disclosed earlier by several inventors.

Improvements in digital freeform generation machines have been disclosed by others, such as Trumper and his group at MIT, for high speed diamond turning[22,23]. A freeform generation machine disclosed by Hof et al. in a patent[24] issued in 2003 appears to be closely related to the older Logan and Brennan machines.

Freeform spectacle surface designs have continued to evolve, in an ongoing effort to provide the best compromise for the wearer, minimizing the unavoidable presence of some surface astigmatism and making the dioptric power variation most comfortable and natural for use. A particularly efficient design method was disclosed by Steele et al. in a patent[25] issued in 2004.

FREEFORM LENSES USED FOR FOCUS ADJUSTMENT

History of freeform use for focus adjustment

Although freeform surfaces were originally suggested for use in spectacle lenses to correct presbyopia, several inventors realized that pairs of freeform lenses could be moved with respect to each other to change the power of a spectacle lens or to adjust the focus in a camera or other instrument. Isao Kitajima, a Japanese physician, obtained a British patent[26] in 1926 for the concept of using two optical devices that could be slid across each other to effect a change in focus. His sliding optical devices were not actually freeforms, but were each comprised of two crossed cylindrical lenses, slightly tapered for gradually changing cylindrical power. If combined algebraically, however, each device was equivalent to a single freeform lens.

Two inventors who soon followed Kitajima described the use of a pair of single freeform lenses that could be slid across each other to change the focus, Birchall[27] in 1938, and Lewis[28] in 1941. Luis Alvarez, a well known physicist, obtained a patent in 1967 for describing the Lewis invention with an algebraic equation[29]. Baker improved on the Alvarez and Lewis variable power lenses by including fifth order or higher order algebraic terms, for better control of spherical aberration, in his 1971 patent[30].

Polaroid Spectra camera

Baker had shown how two freeform optical components can be used within a photographic lens to adjust its focus in a 1984 patent[31]. We realized that freeform surfaces could be used to focus a Polaroid camera as well, not just to view and compose the image. But we knew that sliding objects are mechanically more difficult to manufacture, and that a freeform focus mechanism would be much easier to implement if the motion could be rotary instead of sliding. Two freeform surfaces are used together, one of them moved with a pivoting action across the optical aperture of a lens, as in Figure 8. The pair can change the dioptric power of the lens without introducing coma. This design[32] was disclosed in a patent[33] in 1987.

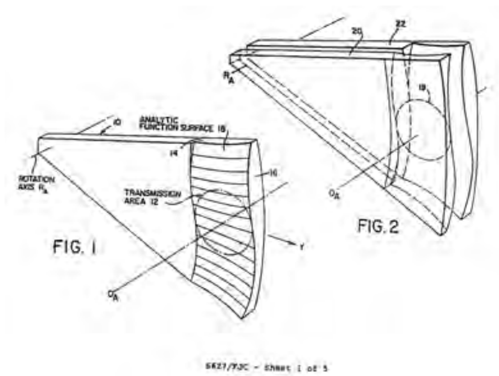

Figure 8. Diagram showing how a pivoted freeform lens is positioned to focus a camera.

Figure 9 shows the picture-taking optical path of the Polaroid Spectra camera, introduced in 1986, beginning with an aspheric meniscus lens on the left. There is a thin mechanical shutter between the small moving lens and the small fixed lens. We called this freeform shape a "Quintic" because our early designs used a fifth-order polynomial description. (Later we used seventh-order and ninth-order polynomials, but didn't want to change the name to "Septic" or "Nontic".)

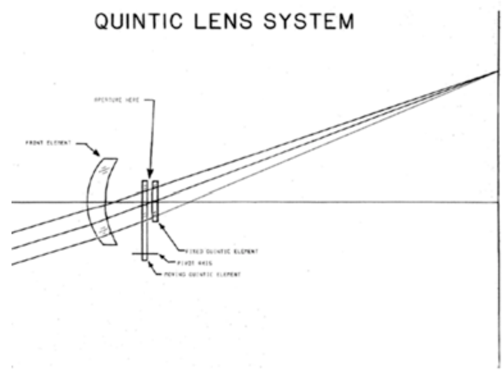

Figure 9. The picture taking optics of the Spectra camera.

Our Spectra camera design gave us ten overlapping zones of focus, illustrated in Figure 10, selected automatically with sonar information. The compact moving part was only about two and a half apertures wide:

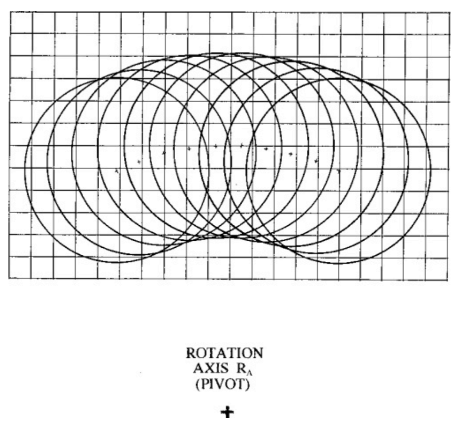

Figure 10. Ten overlapping areas of the Quintic freeform lens are used to focus the Spectra camera. The pivot is at the "+".

Figure 11 shows the shape of the pivoted freeform surface:

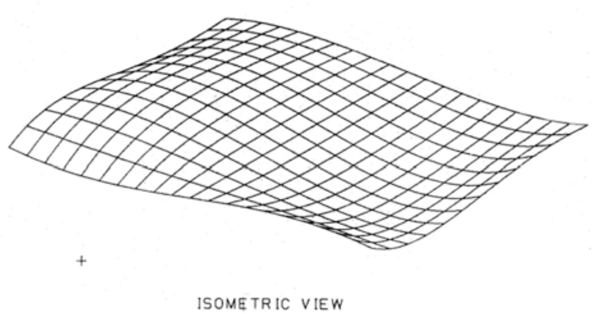

Figure 11. Freeform shape of the pivoted freeform Quintic camera focus lens. The pivot is again marked as "+".

In 1982 we built a profilometer[36] with even greater precision, better than 20 nanometers. This machine was constructed of granite with air-lubricated slides, linear magnetic motors, and laser interferometer control.

Figure 12 displays the molded picture-taking optical parts for the Spectra camera: the aspheric meniscus taking lens, the moving Quintic freeform focus lens, and the fixed Quintic freeform lens. The black frame on the moving freeform lens provides reference holes to identify its angle as it is moved, and notched features to catch it at the desired setting. No focus adjustment is needed when the camera is assembled.

Figure 12. Aspheric and freeform optical parts used in the Spectra camera.

Eyeglasses with two-part freeform lenses

Eyeglasses made with the 1967 Alvarez two-part freeform design were introduced commercially soon after 2005 by the Adlens company[35].

Testing freeform molded shapes and generating freeform molding tools

Molded freeform lenses cannot be checked for quality with simple interferometric test plates, the way we can check spherical lenses. To test our molded freeform surfaces we used an interferometer disclosed by Steve Fantone[36], incorporating a hologram produced optically from the freeform mold surface itself.

We built another granite machine[34] in 1994 for generating freeform optical shapes. Again, we used air bearings, air slides, linear magnetic motors, and laser controls. This machine, shown in Figure 13, measured about 1.5 meters in each dimension.

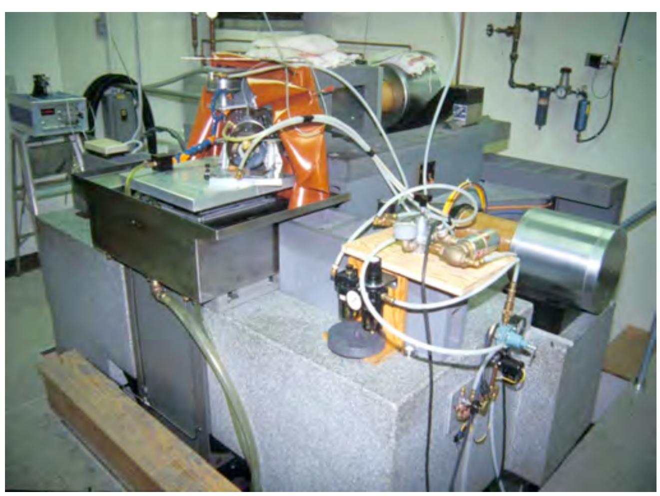

Figure 13. View of precision grinding machine showing linear magnetic motors, air pressure lines, and the grinding spindle used for generating freeform molding tools. The vertical axis motion is supported by a floatation tank beneath it.

This freeform optical Quintic mold shape was ground on that machine. As shown in Figure 14, the surface was smooth enough so that it did not require a polish after the grinding:

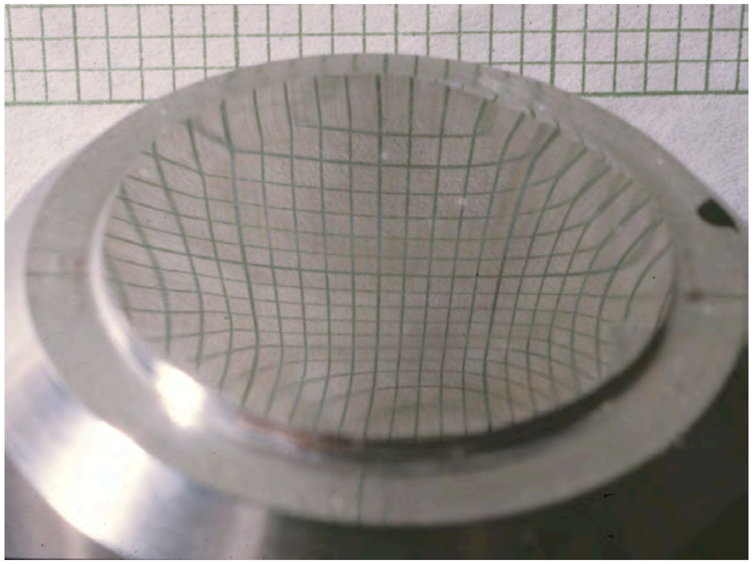

Figure 14. The freeform Quintic molding tool as it is ground to a smooth finish.

Figure 15, taken with a special photon tunneling microscope,[37] shows that the irregularities left after grinding were about 1/10 micron deep, or about 1/4 of a wavelength of light. That "roughness" is only about 100 nanometers. Notice that the vertical scale is much finer than the horizontal scale in the view.

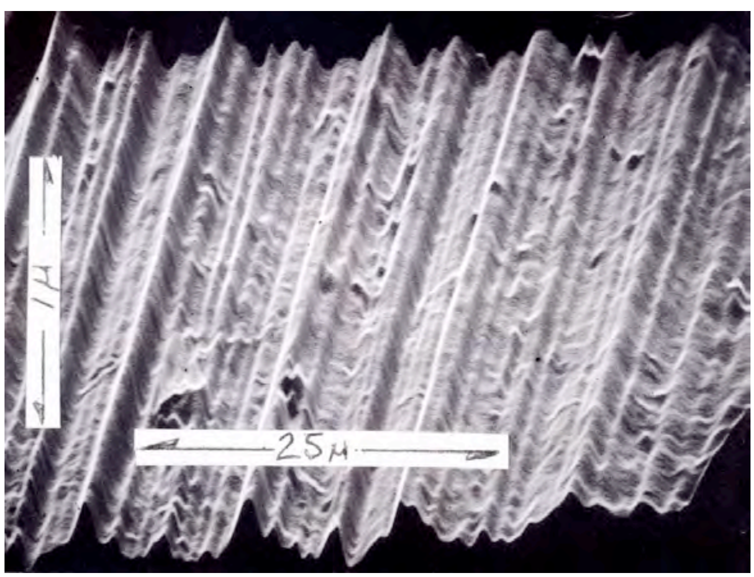

Figure 15. Detail of the ground metal optical surface that does not require further polishing.

This enlarged model of the moving Quintic freeform surface in Figure 16 shows its shape:

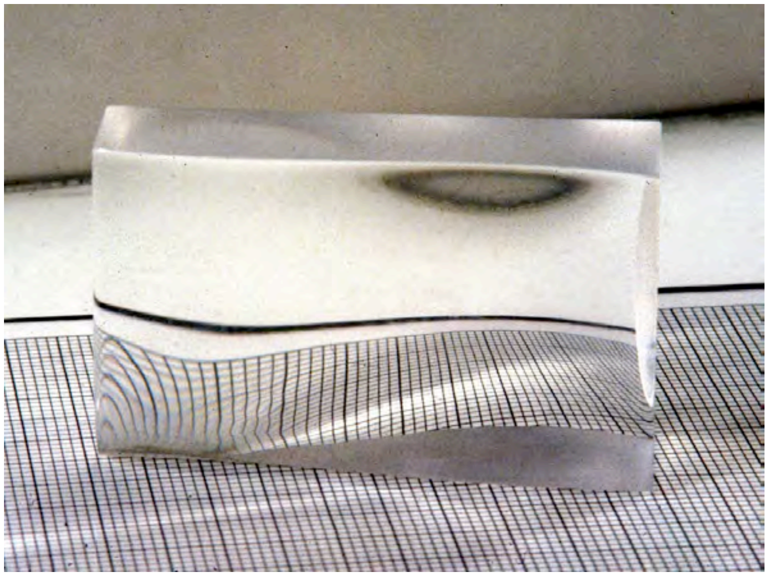

Figure 16. An enlarged model of the moving Quintic focus lens for the Spectra camera.

FREEFORM LENSES USED FOR WAVEFRONT CODING

In 1998 Tom Cathey and Ed Dowski were issued a patent[38] for the use of a freeform optical surface at the aperture stop of a digital camera lens, to increase its depth of field. The image was degraded, but its Modulation Transfer Function could be restored by computation in a way that was consistent over an extended range of defocus. This new capability, called wavefront coding, offered a way to simplify some lens designs as well. In 2006 Tom Cathey was issued a patent[39] for the use of wavefront coding on a contact lens or on an eye implant lens to correct presbyopia. This invention worked reasonably well even without digital correction of the resulting image and offers an improved visual range of about three diopters.

FREEFORM LENSES MOLDED FOR INFRARED WAVELENGTHS

Freeform lenses for use with visible light can be manufactured inexpensively by molding plastics, but the spectral transmission of ordinary plastic and glass is severely limited. Plummer[40,41] devised a new way to mold freeform optical surfaces using materials such as Potassium Bromide and Cesium Iodide, for use in thermal infrared optical systems. The method uses a technology previously considered only for spectroscopic sampling, in which a fine powder of the crystalline material is consolidated into a solid optical part by pressure alone. For making a small lens the pressure can be applied to a mold by a commercially available hand press. This example optical part, illuminated by transmission in Figure 17, has a freeform surface pressed against a US quarter dollar coin. The freeform area is George Washington's cheek. Details of his hair, and some scratches on the coin, show that the technique can be used for manufacturing fine lens arrays and diffractive surfaces as well as freeforms. This finished molded part is polycrystalline, comprised of nano-particles of Potassium Bromide.

Figure 17. Molded freeform optical surface transparent in the infrared to about 20 microns wavelength.

The two optical design examples in Figure 18 provide quite similar and excellent performance. The upper design uses two Germanium lenses with aspheric surfaces. The lower lens, cheaper to make, uses two Germanium lenses with spherical surfaces and a molded potassium bromide lens between them with aspheric surfaces. The molded lens could also include a freeform surface for wavefront coding.

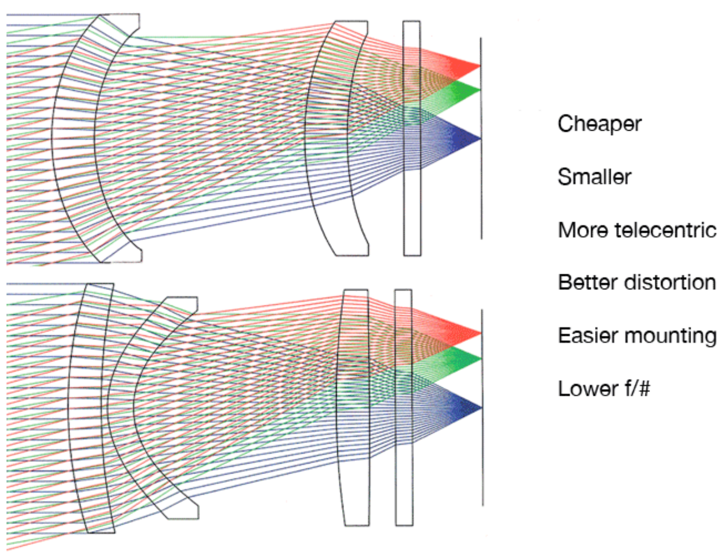

Figure 18. Comparison infrared lens design showing cost reduction with a molded aspheric lens.

An aspheric or freeform lens can be molded from powder in a simple press shown in Figure 19, and an infrared lens can be molded directly into its intended mounting cell[42].

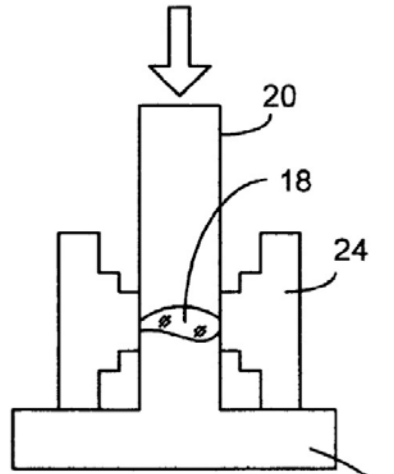

FIG. 6A

Figure 19. A press for molding an infrared freeform lens directly into its mounting cell.

Figure 20 shows how additional optical components can be assembled directly into that same mounting cell[42] after it has functioned as part of the mold.

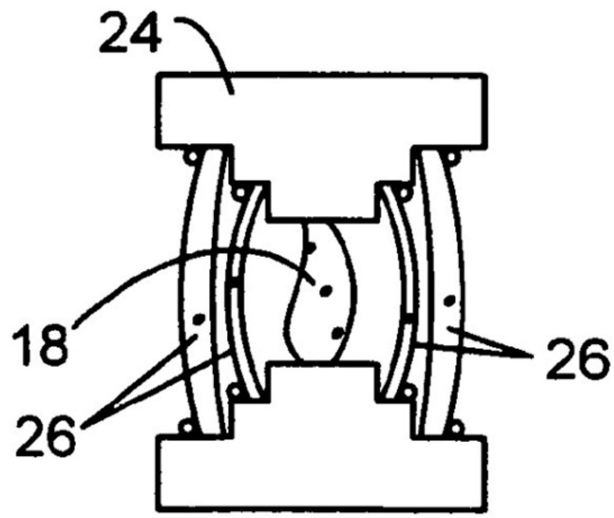

FIG. 6B

Figure 20. An example showing an infrared freeform lens molded into its mounting cell, then combined with other components.

FREEFORM LENSES CAN BE MANUFACTURED BY 3D PRINTING

Nicholas Xuanglai Fang, MIT Professor and co-founder of BMF Material Technology[42], has developed a surprising new process for manufacturing freeform progressive spectacle lenses, and other precise mechanical objects, by 3D printing[43], promising unusual opportunities for customized high-volume production. He and his team developed a technique called projection micro-stereolithography. It is a parallel optical 3D micro/nano fabrication technique. This process fabricates 3D microstructures by cross-linking liquid photopolymers, layer-by-layer, using images generated by a digital data projector[44]. By sequentially presenting the slice images on the digital screen, intricate 3D microstructures, having resolution of a few micro-meters, can be readily constructed as stacks of solidified polymer.

This 3D printing work started with production of complicated mechanical structures of sub-millimeter sizes, with micro-meter precision. But then the technique has been applied for making lenses. The 3D printing method with this high precision can be used to make a large number of small structures at one time, or can make larger objects such as spectacle lenses. Now 3D printing can be used to produce aspheric lenses or any kind of combined lenses with complete design freedom. It can produce modern spectacle lenses that include a freeform progressive shape for correcting a wearer's presbyopia. This large-area additive manufacturing technique can be scaled up for volume manufacturing.

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