Controlling Caustics

Mark Pauly[1], Michael Eigensatz, Philippe Bompas, Florian Rist[2], Raimund Krenmuller[2]
[1] EPFL
[2] TU Wien

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1 = Caustic
2 = Refraction
3 = Reflection
4 = Design
5 = Milling
6 = Slumping

Abstract

Caustics are captivating light patterns created by materials focusing or diverting light by refraction or reflection. We know caustics as random side effects, appearing, for example, at the bottom of a swimming pool, or generated by many glass objects, like drinking glasses or bottles. In this paper we show that it is possible to control caustic patterns to form almost any desired shape by optimizing the geometry of the reflective or refractive surface generating the caustic. A seemingly flat glass window, for example, can produce the image of a person as a caustic pattern on the floor, generated solely by the sunlight entering through that window. We demonstrate how this surprising result offers a new perspective on light control and the use of caustics as an inspiring design element in architecture, product design and beyond. Several produced samples illustrate that physical realizations of such optimized geometry are feasible.

Figure 1 Left: A typical caustic created by a curved glass object appears chaotic and random. Right: Our method creates glass objects that cast controlled caustics by optimization of the glass surface geometry alone. The portrait of Alan Turing emerges from a beam of uniform light that is refracted by the circular glass piece.

Figure 2 Uncontrolled natural caustic patterns. Top Left: Water reflecting onto the side of a boat. Bottom Left: Philippe Bompas - light room experiment 1998. Right: Tokujin Yoshioka - glass bench.

1 Introduction

The interaction of light with glass plays an important role for the perception and functionality of many glass products. One of the most fascinating light phenomena with glass objects are caustics: light gets focused and diverted when passing through the glass, creating an intriguing pattern of varying light intensity. Caustics are ubiquitous but easily overlooked. Once aware of the wondrous effect, one suddenly spots caustics everywhere, for example when cast from a window to the living room wall, or from a wine glass to the dining table (see examples in Figure 1 and 2). Caustics almost without exception appear accidentally, as an unintentional, collateral presence when dealing with glass objects. In this paper we address the following question: How can the intriguing, but uncontrolled nature of caustics be tamed to intentionally cast caustic patterns of arbitrary nature? We will answer this question by introducing a design methodology that allows controlling caustics by shaping the surface of glass objects. Caustics thus become design elements. We propose a corresponding computational tool based on light transport calculations and numerical optimization.

The term *caustic* is derived from the latin word *causticus* and the greek *kaustikos* meaning "burned". In optics, caustics refer to singular concentrations of light that can indeed lead to burns, as anyone who has experimented with a lens in bright sunlight might confirm. In our context, we consider as a caustic a pattern of light on a (mostly diffuse) surface that is created by focusing and diverting light through a glass object (Figure 1, left). To control the shape of a caustic pattern generated by a specular surface, we need to solve the inverse problem: how can we change the surface geometry, such that incident light is redirected to produce a desired caustic image (Figure 1, right). We limit the discussion in this article to refractive caustics created when light passes through a transparent medium such as glass. The same methodology, however, also applies for reflective materials such as polished metals or highly reflective coated glass.
In this paper we wish to present our current results and experiments, as well as illuminate a few of the numerous application possibilities we believe this technology offers. We first give a high-level explanation on the computational method solving the inverse geometric problem

to find a caustic generator surface. We then discuss our current experiments for producing these surfaces from glass and other transparent materials. In the final section we speculate on various application scenarios in architecture, art, product design and beyond, hoping to inspire readers to come up with their own ideas of how this technology can be used in their context.

2 Computation

Inverse caustic design requires advanced computational tools for calculating the surface of the caustic generator. We leverage ideas first presented in the design of optical beam shaping systems and antenna design [1,2]. For more background on the mathematical and computational aspects of our method we refer to [3] and the references therein. Related approaches have also been presented in [4, 5]. In this paper we focus on aspects related to design, application, and fabrication of such glass objects and only provide a brief summary of the computational framework.

We employ a geometric model of optics for our computations. In this model, Snell's law of refraction determines the change of direction of a light ray passing through the interface between two media of different optical density. In our case, this interface is given by the (curved) surface of the glass panel. We assume that the other surface of the glass is flat and that light enters this surface with parallel ray directions (see Figure 3). Parallel incident light is a reasonable assumption for sunlight and artificial light sources sufficiently far away from the object. We show in our experiments that even with spotlights close to the object a good reproduction of the target intensity distribution is achieved. We ignore light dispersion in our simulations, that is, we do not account for the wavelength dependency of the refractive index. Our experiments did not show any noticeable chromatic aberration, which confirms that this simplification is reasonable for our setting.

The geometric setup for our computations is shown in Figure 3. We require a precise specification of the direction of incoming light, as well as the location and orientation of the caustic generator (the glass object) and the caustic receiver. We model the curved surface of the caustic generator as a discrete height field, that is, a regular grid of displacement values over the plane. The desired light distribution on the receiver is specified as a pixel grid of intensity values. Given this intensity profile and the geometric specification of the setup described above, our algorithm solves for the height values of the caustic generator, such that the resulting surface of the refractive object redistributes the incoming uniform light to match the given intensity profile. The solution is obtained by deforming a discrete photon mesh to reproduce a given image. In order to refract rays on the specular surface such that they intersect the receiver at the designated points, we invert the laws of light transport and refraction to adjust the normal field accordingly. Once the surface normals are computed, we solve for the continuous surface that best fits the normal field.

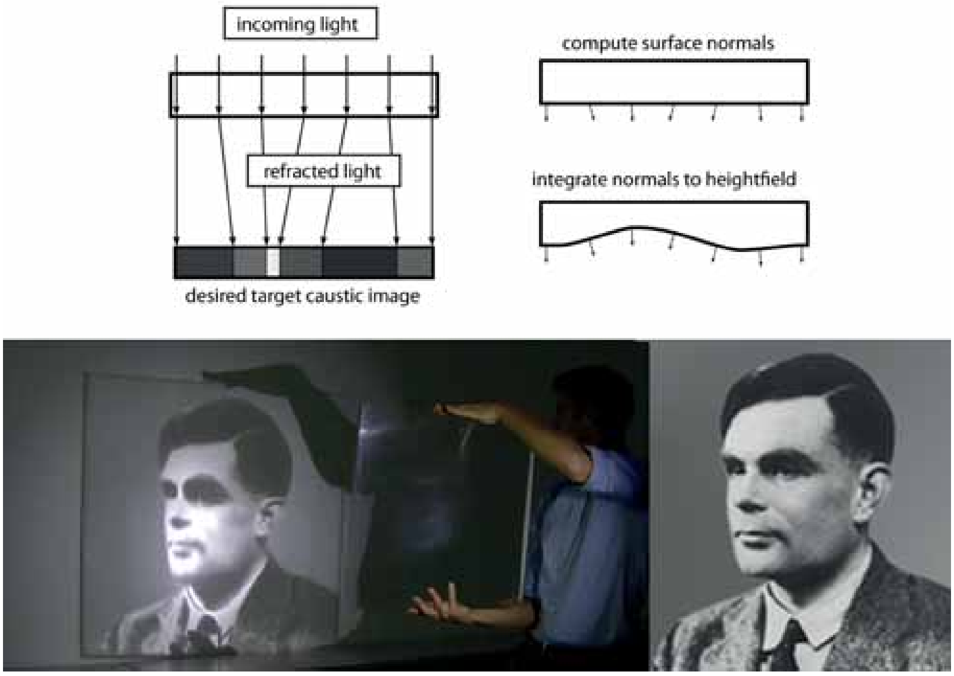

Figure 3 Top: Conceptual sketch of how parallel incoming light is diverted by a glass object to create a desired caustic image. Our algorithm first computes the required surface normals and then integrates the normal field to obtain the curved surface of the glass object. Bottom: A sample of 50cm by 50 cm milled from PMMA and polished by hand to obtain high specularity. When illuminated with uniform light, a caustic image of a portrait of Alan Turing is created (see original photo on the right). Note how the detail of the image is accurately reproduced on the refracted light pattern even though the PMMA plate is just held roughly in position. Even fine-scale detail, such as the weaving of the jacket can be observed.

3 Fabrication Experiments

The creation of accurate and detailed light distributions by refraction requires a manufacturing technology that can create precise freeform surfaces matching the computed height field profiles. We have created a set of physical models to test the calculations and all inherent assumptions and simplifications against real world physics. We decided to experiment with widely available and relatively cheap technologies and not rely on high-end equipment like ultra-precise CNC lathes or mills and diamond cutters as used for example by Brecher at.al [6]. All our samples were machined on a 5-axis machining center, a Spinner U620, Siemens Sinumerik 840D SL. The necessary polishing of the surfaces was performed using a small hand-held tool and suitable grinding and polishing pastes. The produced objects were illuminated either by sunlight or a LED spotlight. Neither of these light sources carries any information on the caustic image that was observed on a planer white screen. The created light pattern is solely due to the curved geometry of the refractive pieces. The surfaces were machined using a ball nose tool and parallel finishing cuts. The tool was tilted by a positive lead angle against the surface. Based on an analysis of the surface features, the maximum tool diameter was chosen to obtain virtually gouging free tool paths. We experimented both with direct machining by milling and grinding, as well as indirect casting using a mold. For both processes we created samples using glass and plastics to evaluate the fabrication processes for different material properties. All samples use the same target caustic image of a portrait of Alan Turing shown in Figure 3.

3.1 Sample 1: PMMA milling

Figure 4 shows the fabrication of an acrylic sample milled from a 500x500x30 mm³ PMMA block. The surface was machined using a 12 mm solid carbide ball nose end mill at a lead angle of 20°, resulting in an effective tool diameter of 4.1 mm. The distance between the paths was 0.2 mm. Total milling time was about 20 hours. After milling, the piece was sanded manually and polished using diamond grinding pastes. The finish was done using a special PMMA polish paste. As illustrated in Figure 5, this sample confirms that the calculated surface does indeed create the intended caustic very accurately. It shows that our system is robust enough to cope well with the simplifying assumptions made in our computational framework, as well as with the manufacturing tolerances and suboptimal lighting.

Figure 4 Milling and polishing of PMMA.

Figure 5 Caustic generated by the milled 500 x 500 mm PMMA Sample 1.

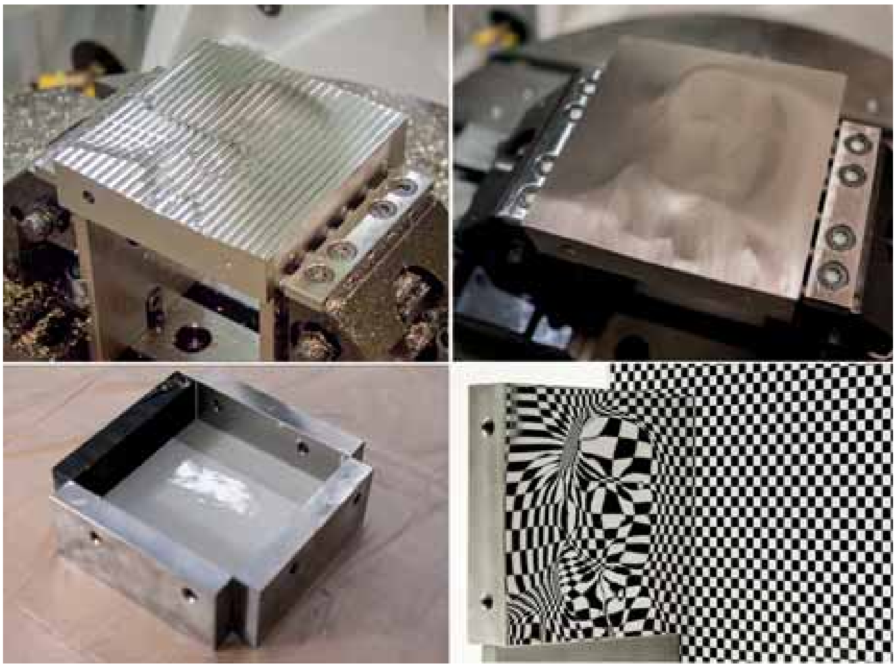

Figure 6 Steel mold. Top Left: first pass. Top Right: finer mill before polishing. Bottom Left: mold assembly. Bottom Right: A checker board is used to visualize the small surface elevations of the mirror polished surface.

3.2 Stainless steel mold for casting.

While the previous sample was directly manufactured, the following experiments evaluate casting processes aimed at mass-production. For this purpose we created a stainless steel mold with a net size of 120x120 mm² (see Figure 6). Despite using a different tool and suitable machining parameters, the steel mold was essentially produced the same way as the PMMA piece.

3.3 Sample 2: Resin cast

The stainless steel mold was first used to cast clear resins (see Figure 7). The main reason for these casts is to test the mold properties with a simple and reliable casting technique. We used smooth-On Clear 221 and Clear Flex, both polyurethane based two-component resins before testing with actual glass.

3.4 Sample 3: Glass grinding

For certain architectural applications PMMA might not be durable enough. Therefore, we conducted a series of experiments to produce caustic generators in glass. While glass is difficult to mill, it is relatively easy to grind, so we slightly adapted the previously used machine to create a 140 mm diameter Schott Borofloat glass sample in the same manner using a standard 8 mm diamond coated ball grinder. As expected, machining and polishing times increased significantly compared to PMMA. Figure 8 shows the result.

3.5 Sample 4: Glass slumping

We did a very basic test to reproduce the caustic generator from glass by molding using slumping. Figure 9 Bottom Left shows a copy of the negative steel mold made from a temperature resistant mold mix. Figure 9 Top shows the results obtained by slumping two different types of glass at a temperature of 870 °C for one hour. While this technique is cheap (as the positive can be made from almost any easy to machine material) it limits the quality of surface reproduction. The overall accessory is good, but the inherit roughness would make time-consuming polishing necessary.

3.6 Discussion of fabrication experiments

In summary, we believe that the samples we have fabricated provide convincing evidence that computational caustics can be realized in the physical world. Despite the simplistic and partly ad-hoc fabrication technology used in our test cases, in particular for glass slumping, the reproduced caustic images match the desired goal images well. With industrial-quality processes, we expect a significant improvement in imaging accuracy. In our view one of the most exciting aspects of this project for future work will be to find new fabrication technologies suitable for controlled caustic reproduction that scale to large glass panels and/or high production volumes.

4 Applications and Design

Computational caustics offer numerous opportunities for new glass products, in particular in the domains of product design, furniture, and architecture. For example, caustic imaging can be used for branding (imagine a company logo being projected by a perfume bottle) or authentication (a security label could become visible when the object is illuminated from a certain angle). This kind of applications do not require any artificial add-on, they can be achieved solely by shaping the surface of glass to re-direct the light appropriately. In architecture, novel façade elements could be designed to channel daylight into building interiors with more precise control over the spatial distribution of light.

Beyond these more technical applications, computational caustics enable a new way of "drawing with light" with numerous opportunities for artistic expression. As mentioned above, natural caustics are ubiquitous as well as usually unintentional, mostly ignored or disregarded. This is partially because their presence is very erratic and tied to a specific light condition that only lets them appear at certain times in a certain form. One needs to contemplate caustics, take the time to wait for them. Designing with computational caustics therefore requires a good understanding of the perception of space and light, and mandates close attention to the geometric configuration of light source, caustic generator, and projection surfaces. One aspect that is particularly intriguing is the variation of the caustic image as the relative position and orientation of caustic generator, incoming light, and/or caustic receivers is modified. For example, caustic images generated by the sun gradually evolve as the sun moves over the sky. This leads to a subtle warping of the caustic image, which will match the input image exactly only for a specific location of the sun. More dramatic changes can be achieved when moving the glass object or when using moving artificial lights (see

Figure 7 Caustic generated by parallel light through the Sample 2 made of cast Resin.

Figure 8 Caustic generated by the sample 3 produced with glass grinding. Insufficient polishing leaves some speckle-noise on the caustic image.

Figure 9 Glass slumping. Top Left: caustic generated by slumped Bullseye glass. Top Right: caustic generated by slumped regular float glass. Bottom Left: fire resistant mix mold with a slump piece. Bottom Right: checker board visualization.

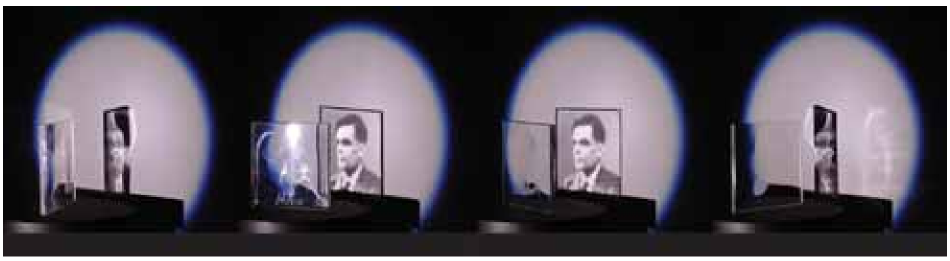

Figure 10 A caustic generator rotating on a turntable with fixed illumination creates interesting dynamic light patterns.

Figure 10). Dynamic installations offer exciting new possibilities for exterior or interior design projects.

5 Conclusion and Outlook

In some way, caustics can be seen as a material property that can now be changed and controlled, almost like the color or finish of a surface. We believe that this surprising result opens up a wide range of applications that we have only begun to discover. The design potential not only lies in the possibility to make an image with light but more generally in new means for light control: being able to produce almost any desired light pattern and focusing light in desired directions and areas offers numerous applications from the graphic use of light to energy control. The scale of caustic design ranges from small consumer or art products, for example, caustic text encoded on a drinking glass, to windows, facade elements, and even to an entire facade itself reflecting or refracting light in a controlled way.

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