On the Brightness in Images Captured with Conventional and Compound Eye Cameras

Todor Georgiev
Adobe Systems Incorporated
345 Park Ave, W10-124, San Jose, CA
tgeorgie@Adobe.com

Abstract

In this paper we consider cameras as belonging to one of two types: single aperture (conventional) cameras, and multiple aperture (compound eye) cameras. The eyes of insects are well known examples of the second type. Recently Fraunhofer Institute announced the manufacturing of a compound eye camera, which is very thin and has potential applications unthinkable for the traditional single lens camera.

In the case of compound eye cameras we describe a fundamental dependence of image brightness on the distance to the object. This is a property not observable in single lens cameras. We derive the mathematical expression for the brightness in images as a function of the distance to the object. Further, we provide an analysis of the behavior of the two types of cameras in this respect. Our conclusion is that compound cameras are fundamentally the appropriate devices for capturing light field information because of their correct sampling of radiance.

1. Introduction

The traditional single aperture camera is modeled after the human eye, and is well studied. In the current paper we are going to analyze this camera from a new perspective that draws a comparison of the behavior of its brightness with the behavior of the brightness in multiple aperture (compound eye) cameras.

Examples of multiple aperture cameras are the compound eyes of insects [1]. There are two types of compound eyes, apposition and superposition. Apposition eyes are made up of thousands of cameras, each one creating a 1-pixel image. Superposition eyes are made up of thousands of telescopes, multiple telescopes contributing to every single pixel.

In this paper we focus our attention on apposition compound cameras [2], for which we derive a new result about Brightness. In nature examples of such cameras are the eyes of some insects, like the dragonfly. Obviously, this result is of interest in Biology. However, our motivation for looking into apposition compound eyes came from analyzing the new camera [3], [4], recently announced by Fraunhofer Institute. This camera is only 0.4 mm thick and can be applied as a thin film onto any surface. It has no moving parts, which makes it very robust.

The other type of camera is the superposition compound eye, found in nocturnal insects and crustations [5]. This type of eye is better adapted to low light environments. Even if the principle of work of this eye is different, it has essentially the same brightness behavior. Superposition compound eyes are also a possible design for future digital cameras [4] and are considered in relation to the Gabor superlens, which uses the arrangement of two grids of microlenses to focus light [6].

From another perspective, the topic of compound eyes is important because of its relation to the theory of the light field [7]. In the widely accepted point of view [7], [8], the light field, or plenoptic function, takes one single value on each ray in 3D. Now, let's assume we observe a point light source. A camera samples light rays, measuring the value of the plenoptic function on each individual ray. Observing our point from 1 foot distance means measuring the value of that function on the same ray as when we observe the point from 10 feet. The brightness of the image point will be the same because the plenoptic function has the same value on the same ray.

From the above counterintuitive example it is clear that our formulation and understanding of the problem needs some refinement. This is one of the goals of the current paper. The proposed formalism naturally leads to analyzing compound eye cameras for which we derive a new result about behavior of brightness with the distance to the object.

2. The Two Mechanisms of Brightness

There are two mechanisms that produce image brightness in a camera. They work together, but are turned on and off differently in single aperture and compound eye cameras. Describing the action of these two mechanisms in different cameras will be our main focus in this paper.

2.1. First Mechanism

A camera observes an object of surface area *A*. If the object is moved closer to the camera, we have exactly the same rays, each coming from the same points on *A*, only now they are forming a bigger image in the camera. (See Fig. 1) We assume that our camera is such that ***the energy flux received by any area in the image is proportional to the total flux radiated from the corresponding area in the object, and does not depend on the distance to the object,*** *d*. This is equivalent to the widely accepted assumption that the light field takes a fixed value on each individual ray, and the camera measures its value. Intuitively, each ray is like a tube, and energy flows through it without crossing the walls.

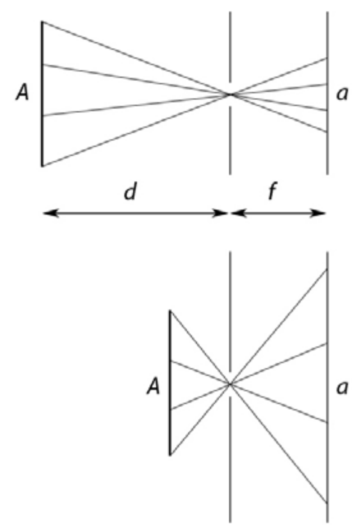

Fig. 1 When object A is close to the camera, the rays fan out to produce image of lower brightness, assuming all other factors equal.

With this assumption, it is clear that image brightness *B* (which is essentially the irradiance at each point) must be proportional to d^2. This result comes from using similar triangles to show that the ratio of lengths of a line element in the object *A* and in its image *a* is equal to the ratio $\frac{d}{f}$. Then, since energy flux is constant along each ray, irradiance (incoming flux per unit area) must be proportional to the inverse ratio of the surface areas, and thus

$$B_1 \propto \frac{A}{a} = \frac{d^2}{f^2} \quad (1)$$

Contrary to what we might have expected for a camera, the closer the object, the less bright the image. Intuitively, the reason is that rays fan out more when the object is close to the camera. The same rays spread over a bigger image and produce less irradiance at each point.

The reason why we see things differently is a specific distortion introduced by our single aperture eyes/cameras, as described next.

2.2. Second Mechanism

Let us see how a fixed aperture camera observes a point source of light. Again, the distance to the aperture is *d*. We consider a pupil with surface area *S*.

In this situation the aperture of the camera is seen from the point light source at a solid angle $\theta = \frac{S}{d^2}$. Assuming continuous distribution of intensity of radiation from the point in different directions, it is clear that the total flux reaching the camera decreases with distance because the angle becomes smaller, and the camera captures smaller portion of the radiated light. Due to that, the final effect is that irradiance, and from here - brightness at a point in a single aperture camera must be proportional to $\frac{1}{d^2}$. For example, in the case of a circular aperture with radius *r* we have $S = \pi r^2$ and the brightness is

$$B_2 \propto \frac{\pi r^2}{d^2} \quad (2)$$

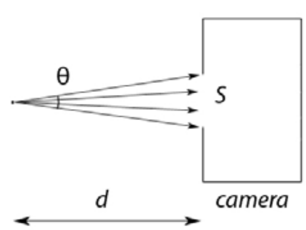

Fig. 2 A fixed aperture camera captures less light as the distance *d* from the light source is increased.

As the camera moves away, it captures smaller and smaller portion of a given light ray. It does not sample the rays of the light field uniformly.

3. Brightness in Single Aperture Cameras

In a single aperture camera both mechanisms 1 and 2 work together, and we get the expected result that brightness is independent of the distance from the object. It depends only on the radius of the aperture *r*, and the focal length f:

$$B = B_1 B_2 \propto \frac{d^2}{f^2}\frac{r^2}{d^2} = \frac{r^2}{f^2} \quad (3)$$

When the object is so far that the size of the image becomes effectively less than a pixel, the first mechanism is turned off, and we get the familiar inverse square expression for the brightness (2).

The first mechanism is turned off only "effectively". One can argue that really the brightness becomes higher, but since it is concentrated on a subpixel area, it gets averaged over a whole pixel inside the camera. Since the total energy is constant and the pixel area is constant, we get no change in measured brightness by focusing the energy into a smaller subpixel spot. That's only one example of how the first mechanism is turned off, and the reader can think of others.

What's more important to note is that there is no physical way to turn off the second mechanism in a single aperture camera. To do that, we would need to increase *r* proportionally to the distance *d*. This is logical impossibility if the camera sees more than one point, since different points can be located at different distances. Still, next section will show that ***mechanism 2 can actually be turned off in compound eye cameras***.

In summary, the image in a single aperture camera has brightness independent of the distance to the object. In case the object in a single aperture camera has image essentially smaller than a pixel, brightness is proportional to $\frac{1}{d^2}$.

4. Brightness in Compound Eye Cameras

4.1. Multiple Aperture (Compound) Cameras.

Multiple aperture cameras were first discovered and studied as the eyes of insects. A compound eye consists of thousands of facets, each one being itself a little camera. Each of those little cameras consists of lenses or mirrors forming the optical system, and a one pixel sensor. In a way, this is like the Light Field camera [9], only each image now is of size 1 pixel. (See however the interesting case of a full Light Field camera as the eyes of the insects known as Strepsiptera [10].)

There are two main types of compound eye cameras, apposition and superposition. Apposition compound eyes are made up of thousands individual single aperture cameras, optically separated from each other. Superposition cameras are made up of one common retina and one common optical system of thousands lenses, or mirrors. The system of lenses consists of thousands of little telescopes packed together, making up the equivalent of a Gabor superlens. A very interesting alternative optical system based on mirrors has been observed in the superposition eyes of the lobster.

4.2. Apposition Compound Camera

A simplified drawing of apposition-type compound camera is shown in Fig. 3. Each little camera, called an *eyelet* (ommatidium), consists of a lens and a sensor (rhabdom), and forms a 1-pixel image. Ommatida are located on the surface of the eye, looking outwards, and displaced from each-other by the interommatidal angle $\Delta\phi$ relative to some center (might not be the center of the eye).

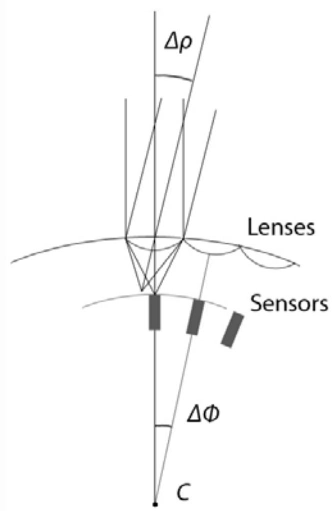

Fig. 3 Apposition compound eye camera

When light comes from a too big angle relative to the optical axis of the individual ommatidium, the image is formed outside the sensor. This defines the acceptance angle, $\Delta\rho$ of individual ommatidium. Note that this angle is measured relative to the optical center located in the lens of each individual ommatidium, which is different from the center *C* of the whole apposition camera. Because of that we can not directly compare the effect of $\Delta\phi$ and $\Delta\rho$.

Ommatida are sensitive only to light rays within the acceptance angle. Rays coming out of a light source located at bigger angles are not detected by the ommatida they reach. This creates the effect of ***pseudopupil***: The light source sees a pupil of the apposition camera no bigger than the acceptance angle $\Delta\rho$. This means that the flux detected by the camera is constant, independent of the distance to the point light source. In other words, ***mechanism 2 is turned off.***

Next we will derive the exact expression on which this effect is based. All angles are small. In Fig. 4 the rays of a point light source reach the camera at distance *d*. The camera is a sphere of radius *R*. The observed pseudopupil has radius *r*. It is described by the last ray that can be detected, at angle $\theta = \frac{r}{d}$. This ray reaches the camera at angle ϕ measured from the centre, where $\phi = \frac{r}{R}$. From the definition of acceptance angle $\Delta\rho$ we have $\theta + \phi = \Delta\rho$.

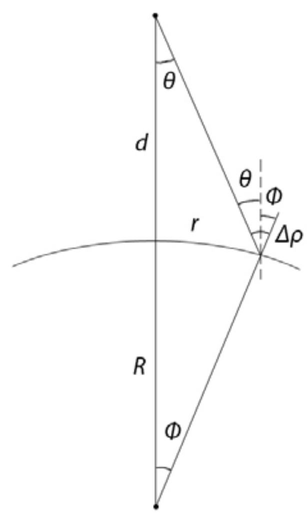

Fig. 4 Geometry of the derivation of equation 4.

After we substitute θ and ϕ we get

$$\frac{r}{d} + \frac{r}{R} = \Delta\rho$$

from which we derive our final expression for the radius of the pseudopupil:

$$r = \frac{\Delta\rho}{\frac{1}{d} + \frac{1}{R}} \qquad (4)$$

Two limit cases are of interest. For far away objects *d* is big and (4) becomes $r = \Delta\rho\, R$. This is the case of fixed aperture and constant brightness of, exactly like in single aperture cameras.

For close by object, *d* is small, and (4) becomes

$$r = \Delta\rho\, d \qquad (5)$$

The radius of the pupil is proportional to the distance. This turns off mechanism 2, and makes brightness proportional to distance squared (1). That's how small insects see close by objects.

A special case is when close by objects are really small so that mechanism 1 is also turned off. Then brightness is constant.

As an illustration of this result we show two pictures of a dragonfly (Fig. 5), taken from two different distances, both small. Note that the pseudopupil is approximately the same size while the dragonfly is bigger when the picture is taken from smaller distance. As expected, we did not observe this behavior of the pseudopupil at big distances.

Our pictures should not be considered rigorous experimental confirmation of (5), but rather an illustration of how images should behave in the experiment.

Fig. 5 The pupil of a dragonfly should remain the same size when picture is taken from a different distance *d* (small distances).

4.3. Superposition Compound Camera

Nocturnal insects and crustaceans that live in lower lighting conditions typically have superposition compound eyes. Superposition cameras are more efficient in capturing light. The optical system consists of two layers of lenses forming an array of telescopes. Alternatively, in the case of the lobster, it is an array of mirrors.

Without going into details, we will mention that the optical system of thousands telescopes of insect eyes is very similar to the Gabor superlens, and will use the result for aperture of superlenses [6]. A superlens consists of 2 arrays of lenses placed on two parallel planes, small distance from one-another. Usually this distance is the sum of the focal lengths of the two types of lenses. This distance is small, and the two planes are viewed as one thin plate. Let's denote the distance from a superlens to the object by *d*. If the focal lengths of the first and second layer of lenses are f_1 and f_2, and the pitch of the lenses in the first and second array is respectively p and $p + \Delta p$, the radius of the effective aperture is shown in [6] to be

$$r = \frac{p\, d}{2(f_1 + f_2 + \frac{\Delta p\, d}{p})} \qquad (6)$$

This expression is of the same form as our result (4) for apposition compound cameras. Again, in the limit of small *d* we have linear dependence of pseudopupil radius on the distance

$$r = \frac{p\, d}{2\, f} \qquad (7)$$

where $f = f_1 + f_2$ is the distance between the two layers of lenses. Note the similarity between (7) and (5).

The same is true for the mirror system superposition eye of the lobster (Fig. 6). Each ray is reflected from the corresponding mirror before it reaches to the sensor. If however the angle at which the ray reaches the mirror is bigger than some critical acceptance angle $\Delta\rho$, the ray will be reflected two times or more, and will go in a wrong direction. (Most likely it will be absorbed.)

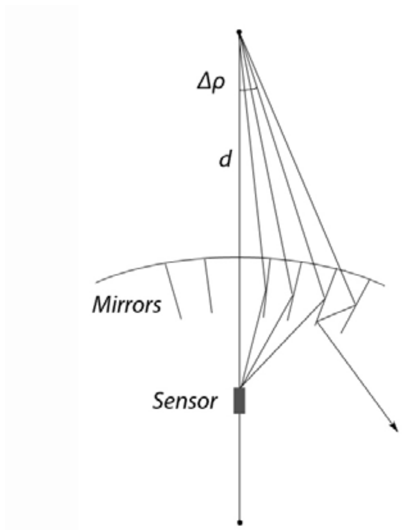

Fig. 6. Acceptance angle $\Delta\rho$ in the eye of the lobster.

Just as in as in the apposition eye, we have rays reaching the eye and not detected if the angle is bigger than certain value. The geometry is exactly the same. The derivation and the final result for the radius of the pseudopupil will be as in the case of equations (4) and (5). Mechanism 2 is turned off and observed brightness of a point light source is independent of the distance.

Conclusion

This paper has described the two types of cameras in relation to dependence of image brightness on the distance to the observed object. We have found that the familiar behavior of single aperture camera is not appropriate for sampling the light field. This is related to the fact that it captures smaller portion of the ray with the increase of distance, as described in the second mechanism.

We have derived a new expression for the radius of the aperture of compound eye cameras. This aperture is different for objects at different distances in the same scene at the same time. Because of that property, such camera is able to measure correctly the same value for the energy flux of a ray, no matter where on the ray it is placed.

The above behavior is due to the unique ability of compound cameras to capture the rays coming out of a point in a small solid angle, where this angle does not depend on the distance to the point. In this way, the camera integrates over all rays in a little 4D space-angle volume, as is appropriate for sampling the radiance. This is the unique property of compound cameras, which makes them the appropriate devices to sample light field density.

References

1. G. A. Horridge. The compound eye of insects. *Scientific American* 237, 108-120, July 1977.

2. J. S. Sanders and C. E. Halford. Design and analysis of apposition compound eye optical sensors. *Optical Engineering*, Vol. 34, No. 1, 222-235, January 1995.

3. J. Duparre, P. Schreiber, P. Dannberg, T. Scharf, P. Pelli, R. Volkel, H. Herzig, A. Brauer. Artificial compound eyes – different concepts and their application to ultra flat image acquisition sensors. *Proc. SPIE 5346,* San Jose, USA, January 2004.

4. J. Duparre, P. Dannberg, P. Schreiber, and A. Brauer. Micro-optically fabricated artificial apposition compound eye. *Proc. SPIE 5301,* 25-32, San Jose, USA, January 2004.

5. J. Duparre, P. Schreiber, and R. Volkel. Theoretical analysis of an artificial superposition compound eye for application in ultra flat digital image acquisition devices. *Proc. SPIE 5249,* 408-418*,* San Jose, USA, January 2004.

6. C. Hembd-Solner, R. F. Stevens, and M. C. Hurtley. Imaging properties of the Gabor superlens. *J. Opt. A: Pure Appl. Opt.* 1 (1999) 94-102.

7. M. Levoy and P. Hanrahan. Light field rendering. *Proceedings of ACM SIGGRAPH 1996,* 161-170.

8. E. H. Adelson and J. R. Bergen. The plenoptic function and the elements of early vision. *In Computation Models of Visual Processing,* M. Landy and J. Movshon, eds. 3-20, MIT Press, Cambridge, 1991.

9. J. Yang, M. Everett, C. Buehler, L. McMillan. A real-time distributed light field camera. *Eurographics Workshop on Rendering,* 1-10, 2002.

10. W. Pix, J. Zanker and J. Zeil. The optomotor response and spatial resolution of the visual system in male Xenos Vesparum (Strepsiptera). *The Journal of Experimental Biology* 203, 3397-4302. 2000.

Adobe Systems Incorporated • 345 Park Avenue, San Jose, CA 95110-2704 USA • *www.adobe.com*

95000289

3/03