Cameras and Light Fields 10

CS184: Computer Graphics and Imaging

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1 Cameras and Lenses

1.1 Terminology

When dealing with cameras and lenses, it is easy to get bogged down by the various terms and mix up how they all relate to one another. Some have direct relationships, while others have inverse relationships, and so on. Let's start by defining the terminology that we commonly use when talking about cameras and lenses.

1. Briefly define each of the following terms in your own words. Where applicable, also draw an accompanying diagram to help explain the concept.
   (a) Focal length
   (b) Field of view
   (c) Exposure
   (d) Shutter speed
   (e) Aperture
   (f) F-stop
   (g) Circle of confusion
   (h) Depth of field

Solution:

(a) Focal length: the distance between the center of a lens and the point at which parallel light rays from infinity at brought into focus

(b) Field of view: the extent of the scene that is visible to the camera's sensor, measured as an angle

(c) Exposure: determines how light or dark an image will appear and is determined by three settings: aperture size, shutter speed, and ISO (gain)

(d) Shutter speed: how quickly the shutter opens and closes for the sensor to capture light; the reciprocal of the how long the shutter is open for during a capture

(e) Aperture: the size of the opening through which light enters the camera and hits the sensor or film

(f) F-stop: the ratio between the focal length and aperture size for a given camera configuration

(g) Circle of confusion: a spot caused by a cone of incoming light rays from a lens that do not come into perfect focus; the less in focus, the larger the circle of confusion

(h) Depth of field: the range of depths that are in focus for a given camera configuration (e.g. the farthest depth in focus - the closest depth in focus)

1.2 Configurations and Effects

1. Assuming focal length is the distance between the sensor and lens, how are focal length and field of view related? For a fixed sensor size, how does increasing focal length affect field of view?

   Solution: Focal length and field of view are inversely related. A shorter focal length results in a wider field of view, while a longer focal length results in a narrow field of view.

2. An image captured with a 50mm focal length is considered to have a "normal" field of view. What about an image taken with a 15mm focal length? How about 150mm focal length? Do these types of images have special names?

   Solution: An image taken with a relatively shorter focal length such as 15mm is called wide angle. An image taken with a relatively longer focal length such as

150mm is called a telephoto.

3. Which of the following camera configurations has the smallest field of view?
   (a) 36mm wide sensor and 50mm focal length lens
   (b) 12mm wide sensor and 18mm focal length lens
   (c) 24mm wide sensor and 8mm focal length lens

Solution: Recall that the field of view can be computed as an angle:

$$\text{FOV} = 2\text{arctan}(\frac{h}{2f})$$

where h is the sensor size and f is the focal length.

Using this expression, we see that (a) has FOV $2\text{arctan}(\frac{36}{100})$, (b) has FOV $2\text{arctan}(\frac{12}{36})$, and (c) has FOV $2\text{arctan}(\frac{24}{16})$. (c) has the largest FOV at approximately 56.31 degrees, whereas (a) has FOV 19.8 degrees and (b) has FOV 18.43 degrees.

4. How are sensor size and field of view related? What happens to the field of view if I don't move my sensor, but increase its size? What about decreasing its size?

Solution: Sensor size and field of view are directly related to each other. A larger sensor size will result in a larger field of view, and vice-versa.

5. If my F-number is increasing, then what can I deduce about the size of my aperture and/or my focal length?

Solution: F-number is defined as the ratio of focal length to aperture size. Thus, if my F-number is increasing, then either my focal length is increasing relative to my aperture size. This could happen if I increase my focal length while holding aperture size constant or if I decrease my aperture size while holding my focal length constant.

6. To help reduce motion blur when I capture photos, I can increase the shutter speed of my camera (which reduces the amount of time the sensor is exposed to light). What are the tradeoffs of doing so? What can I do to mitigate the tradeoffs?

Solution: Recall that exposure is the product of exposure time and irradiance. Increasing shutter speed reduces exposure time, so our overall exposure value is lower. This means that our images will become darker in exchange for reducing the effects of motion blur. To counteract this, we can attempt to boost the amount of irradiance falling on the sensor by increasing the size of our aperture by a proportional amount.

7. How are depth of field and aperture size related? What happens to the depth of field if I reduce the size of my aperture? What else happens if I reduce the size of my aperture?

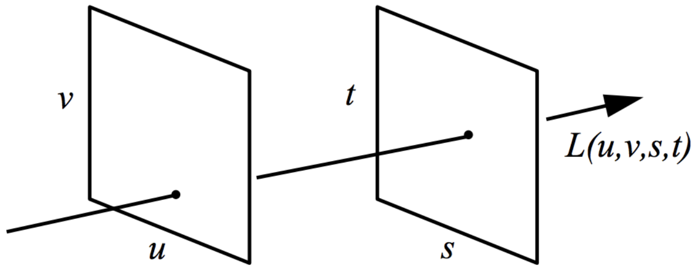
Solution: Depth of field and aperture size are inversely related. A smaller aperture size will result in a larger depth of field (a larger range of depths in the image will be in focus). Conversely, a larger aperture size will result in a smaller depth of field. However, as we saw above, aperture size is directly proportional to exposure, so reducing the aperture size will increase depth of field at the tradeoff of having a darker image.

8. Briefly explain why photographers must choose between depth of field and motion blur for moving objects.

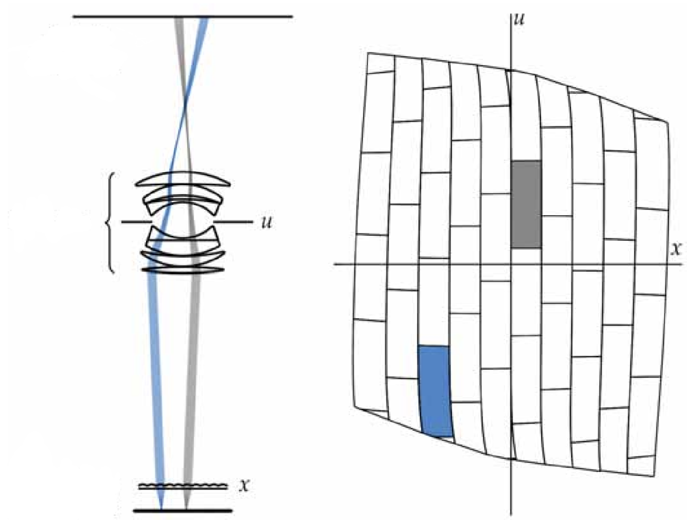
Solution: To gain better depth of field, photographers must reduce the size of their aperture when taking photos. However, this means that less light will reach the sensor. In order to maintain roughly the same amount of exposure that the sensor gets, photographers then need to also decrease their shutter speed, which could introduce motion blur into their photos. The opposite tradeoff also holds true.

2 Light Field Parameterization

A light field is a function describing the radiance along each ray. One of the most common ways to represent this is the two-plane parameterization (also called the light slab representation), where each ray is parameterized by its intersection points with two fixed planes in space.



1. In the diagram of a plenoptic camera below, which two planes define the light field parameterization? Which components of the camera determine the sampling resolution for each of these planes?



> **Solution:** The two planes that parameterize the light field sampled in a plenoptic camera are the camera aperture plane and the microlens plane. The sampling resolution of the aperture plane is determined by the number of pixels under each microlens, and the sampling resolution of the microlens plane is determined by the number of microlenses.

2. A slice of the sampled light field at a single location on the u plane in the plenoptic camera diagram is typically called a sub-aperture image. Describe in your own words what this slice of the light field represents and how it should appear.

> **Solution:** This represents an image taken with a pinhole camera where the pinhole location is the specific point on the u plane. It should look like an image of the scene with infinite depth of field. Different sub-aperture images can be considered as images of the same scene from different viewpoints.

3 Computational Refocusing

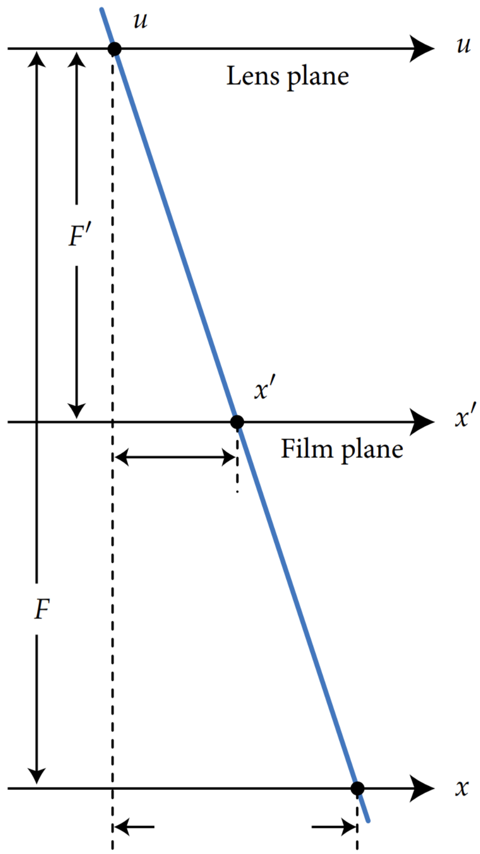
A conventional image records the irradiance on the sensor plane. This can be expressed as an integral of the radiance entering the camera through the lens as:

$$E_F(x, y) = \frac{1}{F^2} \int \int L_F(x, y, u, v) du dv \tag{1}$$

where F is the separation between the exit pupil of the lens and the sensor, E_F is irradiance on the sensor plane, L_F is the light field inside the camera body, and the optical vignetting cosine falloff factor has been absorbed into the definition of the light field for simplicity.

Refocusing the recorded image to a different depth corresponds to changing the separation between the lens and sensor planes. We can derive an equation for the image refocused to a new sensor depth F' by expressing the camera body light field $L_{F'}(x', y', u, v)$ in terms of the original light field $L_F(x, y, u, v)$. Note that only the x and y coordinates of the light field are being reparameterized because we are just moving the sensor plane and not the aperture plane.

1. Derive an expression for the re-parameterized camera body light field $L_{F'}(x', y', u, v)$. The figure below visualizes the relevant similar triangle relationship necessary for this derivation.



Solution:

$$L_{F'}(x', y', u, v) = L_F(u + \frac{x' - u}{\alpha}, v + \frac{y' - v}{\alpha}, u, v) \tag{2}$$

$$= L_F(u(1 - \frac{1}{\alpha}) + \frac{x'}{\alpha}, v(1 - \frac{1}{\alpha}) + \frac{y'}{\alpha}, u, v) \tag{3}$$

where we define $\alpha = \frac{F'}{F}$.

2. Combine this derivation of the reparameterized camera light field with the imaging equation that expresses the recorded image as the irradiance on the sensor plane to derive the computational refocusing equation that expresses how the recorded light field can be reparameterized and integrated to compute images refocused to different depths.

Solution:

$$E_{F'}(x', y') = \frac{1}{\alpha^2 F^2} \int \int L_F(u(1 - \frac{1}{\alpha}) + \frac{x'}{\alpha}, v(1 - \frac{1}{\alpha}) + \frac{y'}{\alpha}, u, v) du dv \tag{4}$$